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Charts for Estimating Fire Behavior

Jim Davis

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CHARTS FOR ESTIMATING FIRE BEHAVIOR

by

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CHARTS FOR ESTIMATING FIRE BEHAVIOR

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INTRODUCTION

An analytical model by Rothermel[1/] for predicting rate of fire spread and intensity is the basis for the National Fire-Danger Rating System.[2/] Tables containing fire-danger rating indicies are prepared from the fire model predictions. The formulae behind the tables are complicated and generally too combersome to be calculated by hand. So the tables were developed to allow users to progress quickly from environmental data to fire-danger rating indices.

This document shows users how to predict fire behavior rapidly from environmental data to intensity, rate-of-spread, and flame length using only a straightedge and pencil. Stylized fuel models are used for this purpose.

1/ R.C. Rothermel. A mathematical model for predicting fire spread in wildland fuels. USDA For. Serv. Res. Pap. INT-115, 40 p. 1972.

2/ John E. Deeming, James W. Lancaster, and others. National Fire-Danger Rating System, USDA For. Serv. Res. Pap. RM-84, 165 p., illus. 1972.

A guide to fuel model selection, taken largely from the National Fire-Danger Rating System, is given in Appendix A and the models themselves are detailed in Appendix B. The mathematical basis for the nomographs is the rate-of-spread model,[3] with minor modifications as outlined in Appendix C.

The fire behavior described by the nomographs pertains to the leading edge of a spreading surface fire. It does not include spread by spotting (firebrands or embers), crown fire (spread through coniferous tree crowns), or the long term residual fire intensity.

Comments on the utility and accuracy of these charts and models are solicited from all potential users.

HOW TO USE THE NOMOGRAPHS

1. Determine the appropriate fuel model to use. See the selection guide in Appendix A. This guide is taken largely from the National Fire-Danger Rating System[4] selection guide because the fuel models are very similar to those used in the NFDRS.

2. Determine the environmental factors: windspeed, terrain-slope, and fuel moistures. A working chart is provided for each fuel model in the lower left-hand quadrant, which allows one to combine the measured 20-ft windspeed and the terrain-slope tangent to obtain an "effective windspeed." The procedure is explained in the text accompanying the chart on each figure.

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[3] Rothermel, op.cit.

[4] Deeming, op.cit.

Fuel moisture for the dead fuel components can be taken from Fire-Danger Rating assessments, fuel stick measurements on site, or from any other appropriate source. For models A, B, C, E, F, G, H, and L, use the 1-hour timelag fuel moisture. For models D and M, if the data are available, combine the three moisture contents as follows:

"Dead Fuel Moisture" = 0.89 X (1-hour timelag moisture)
+ 0.09 X (10-hour timelag moisture)
+ 0.02 X (100-hour timelag moisture)

For the slash models, I, J, and K, combine the three moisture contents as follows:

"Dead Fuel Moisture" = 0.76 X (1-hour timelag moisture)
+ 0.18 X (10-hour timelag moisture)
+ 0.06 X (100-hour timelag moisture)

Live fuel moisture (foliage moisture) is required for models B, C, D, F, and G. If data are unavailable for estimating such moisture, the following rough estimates based on the stage of the dominant cover species in its annual cycle can be used:

300 percent--Fresh foliage, annuals developing, early in growth cycle.

200 percent--Maturing foliage, still developing, with full turgor.

100 percent--Mature foliage, new growth complete and comparable to older perennial foliage.

50 percent--Entering dormancy, coloration starting, some may have dropped from stems.

3. Proceed to calculate fire behavior using the nomograph with the appropriate effective windspeed range.

A. Enter the nomograph, via the upper right-hand scale, at the appropriate "Dead Fuel Moisture." Draw a horizontal line across the page at that point.

If only dead fuel is present in the fuel model, determine the point of intersection of this horizontal line with the S-shaped curve in the upper right-hand quadrant. From this point of intersection, draw a vertical line down through the lower right-hand quadrant. Call this "line A." Go to step B.

If both live and dead fuels are present in the fuel model, determine the point of intersection of the horizontal line with the curve in the upper right-hand quadrant, which corresponds to the live fuel moisture (foliage). Interpolate if necessary. These curves are labeled and also distinguished by the dot-and-dash patterns. From this point of intersection, draw a vertical line down through the lower right-hand quadrant. Call this "line A." Continue the horizontal line through the upper left-hand quadrant, connecting it to the "Dead Fuel Moisture" scale on the upper left-hand scale at the same value used to enter the nomograph on the upper right-hand scale.

Note the curves in the upper left-hand quadrant. They are labeled with the various live fuel moistures and are drawn with the same dot-and-dash patterns as their corresponding curves in the upper right-hand quadrant. If the horizontal line intersects the curve in the upper left-hand quadrant for the live fuel moisture being used, then draw a straight line from this point of intersection to the lower right-hand corner of this quadrant. Call this "line K." You will use this constructed line later, in step D. If the horizontal line does not intersect the curve of live fuel moisture being used, you will not need to use a constructed line in step D. Proceed in either case to step B.

B. Line A, constructed in step A, extends vertically down into the lower right-hand quadrant, crossing the lines labeled "Effective Windspeed" in that quadrant. You should already have determined the value of the effective windspeed using the small graph inset in the lower left-hand quadrant. If not, do so before proceeding. (The instructions are printed below the graph on each page.) Determine the point of intersection of the vertical line with the line labeled with the value of the effective windspeed, interpolating if necessary. From this point of intersection, draw a horizontal line across the bottom of the nomograph, extending through the lower left-hand quadrant.

C. Determine the point of intersection of the horizontal line constructed in step B with the diagonal line in the lower left-hand quadrant. From this point of intersection, draw a vertical line into the upper left-hand quadrant, passing through the lines drawn in that quadrant.

D. If only dead fuel is present in the fuel model, then determine the point of intersection of the vertical line constructed in step C with the line labeled with the appropriate 1-hour timelag fuel moisture, interpolating if necessary. From this point of intersection, draw a horizontal line back through the upper right-hand quadrant. Call this "line D." Proceed to step E and read results.

If both live and dead fuels are present in the fuel model, then the next step depends upon whether or not you constructed line K in step A. If line K was constructed, determine its intersection with the vertical line constructed in step C. From this point of intersection, draw a horizontal line back through the upper right-hand quadrant. Call this "line D." Proceed to step E and read results. If you did not have to construct line K in step A, then locate the curve labeled with the value of live fuel moisture used in step A, interpolating if necessary. From where this curve intersects the vertical line constructed in step C, draw a horizontal line to the right, through the upper right-hand quadrant. Call this "line D."

E. Results can be read at three places:

1. Line A crosses the horizontal axis separating the two right-hand quadrants. Read the scale at that point to determine the reaction intensity of the fire.

2. Line D crosses the vertical axis separating the two upper quadrants. Read the scale at that point to determine the forward rate of spread of the fire.

3. Line A (extended upward if necessary) and line D intersect in the upper right-hand quadrant. The flame length at the front of the fire can be determined at this intersection point. Interpolate between the hyperbolic curves (those that run from upper left to lower right in a rounded L-shape), which are labeled with the values of flame length.

EXAMPLE 1

In the late fall, after most of the leaves have fallen, but before any significant compacting of the leaf litter, a fire is reported on a steep (50 percent) slope in a dense Pin Oak grove. There is a 10 mph wind in the area, and the calculated 1-hour timelag fuel moisture for the day is 5 percent. Determine the expected intensity, rate of spread and flame length.

Steps in Solution:

1. From the selection guide determine that the appropriate fuel model is E. Turn to the page with Model E, for low windspeeds.

2. Using the chart inset in the lower left-hand quadrant, determine the "effective windspeed" as shown in the accompanying figure, labeled "step 2." The effective windspeed is 12.5 mi/hr.

3. The steps outlined above are displayed in the accompanying chart, labeled 3a-through 3d. The results, read from the example chart, are:

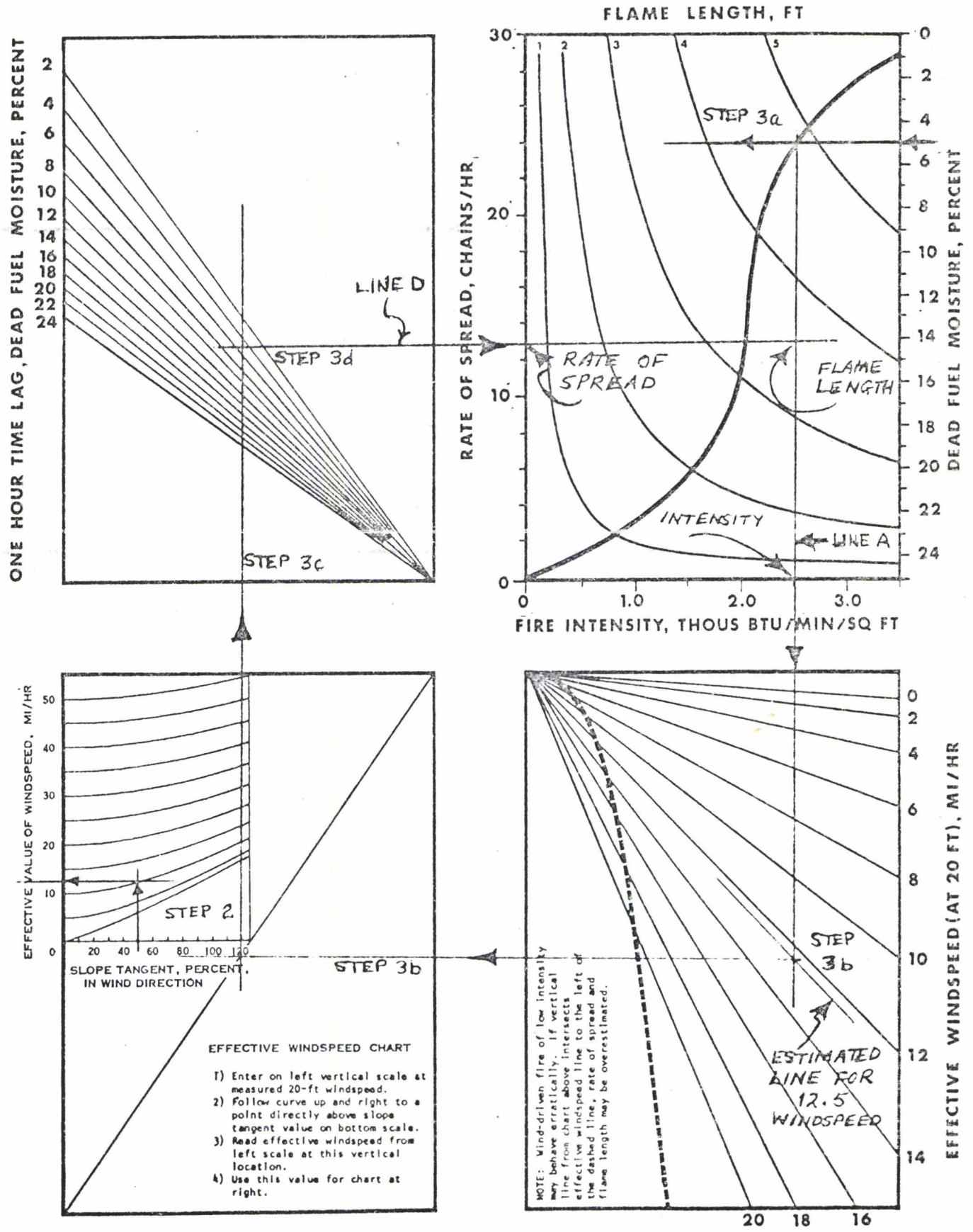
Intensity = 2.5 thous Btu/min/sq ft

Rate of spread = 13 chains/hr

Flame length = 3.5 ft

E. HARDWOOD LITTER - LOW WINDSPEEDS

EXAMPLE 1



EXAMPLE 2

In mid-June, under very high wind conditions, a fire is reported in a dense stand of mixed chaparral on low,rolling hills. A 40-mi/hr wind is reported nearby. Today's fire-danger rating sheet gives the 1-hour timelag fuel moisture as 7 percent. Because of the time of year and the appearance of the foliage, you estimate the live foliage moisture content to be 100 percent. Determine the expected intensity, rate of spread, and flame length.

Steps in Solution:

1. From the selection guide, determine that the appropriate fuel model is B. Turn to the page with Model B, for high windspeeds.

2. Since the slope is near zero, the effective windspeed can be taken to be 40 mi/hr, as measured. The fuel moistures were mentioned above.

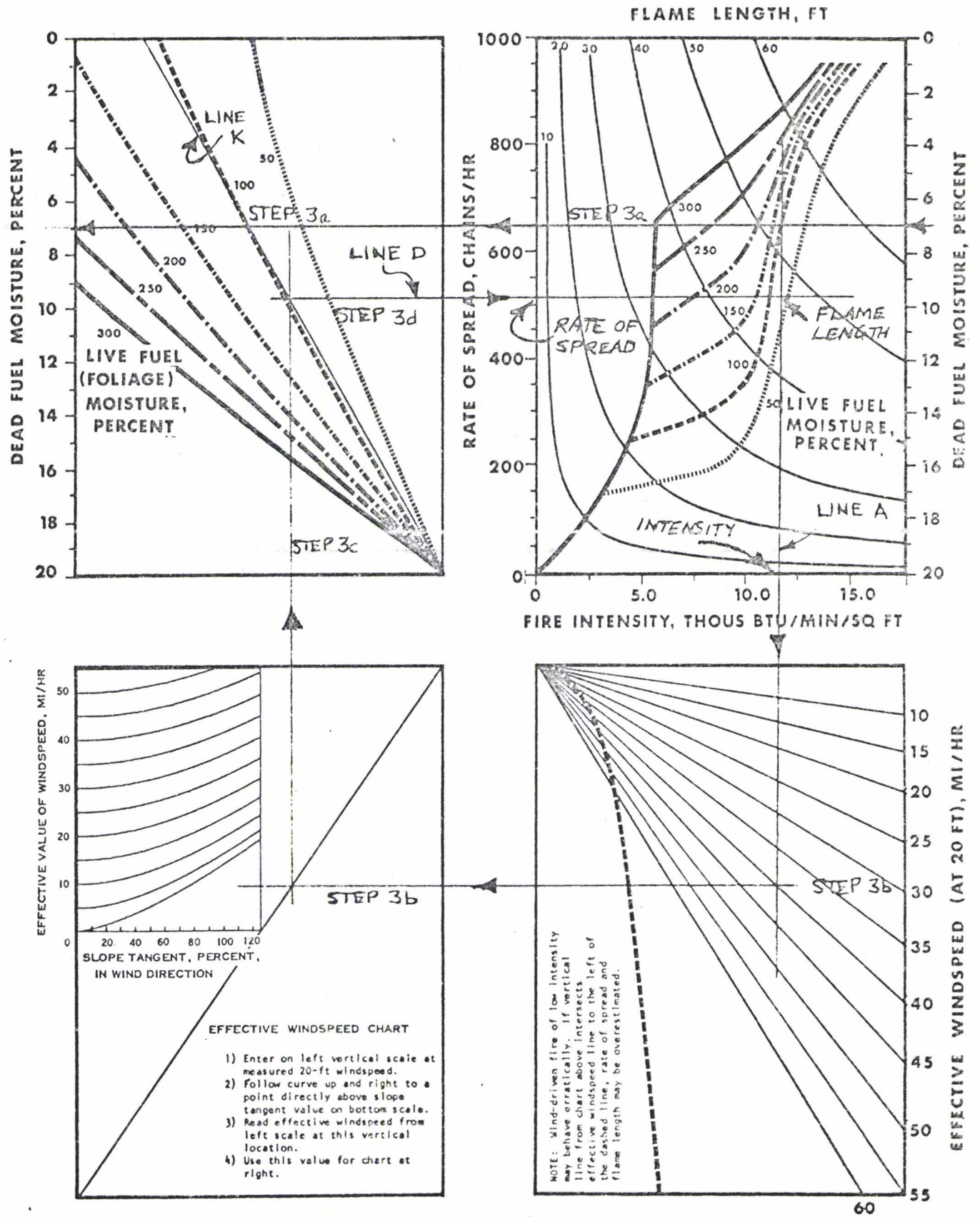
3. The steps outlined above are displayed in the accompanying figure, labeled "step 3a" through "step 3d." The results, read from the example chart, are:

Intensity = 11.5 thous Btu/min/sq ft

Rate of spread = 445 chains/hr

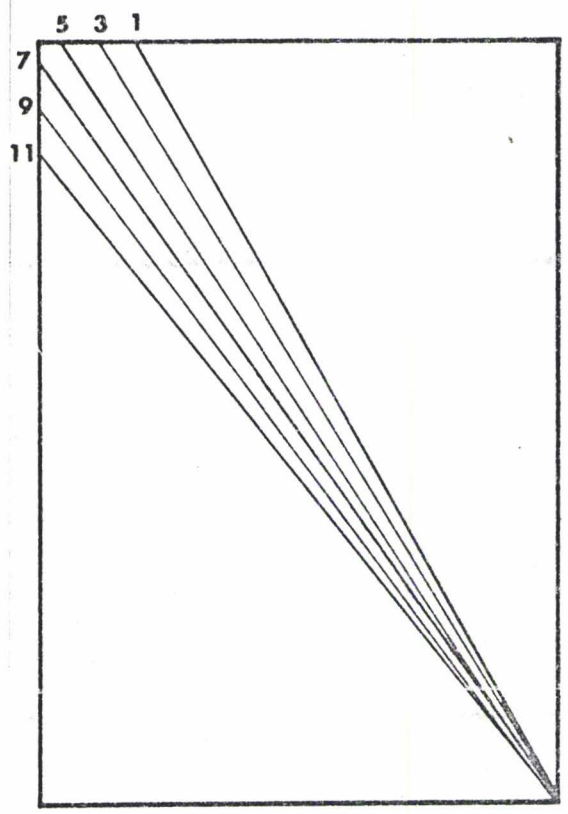
Flame length = 46 ft

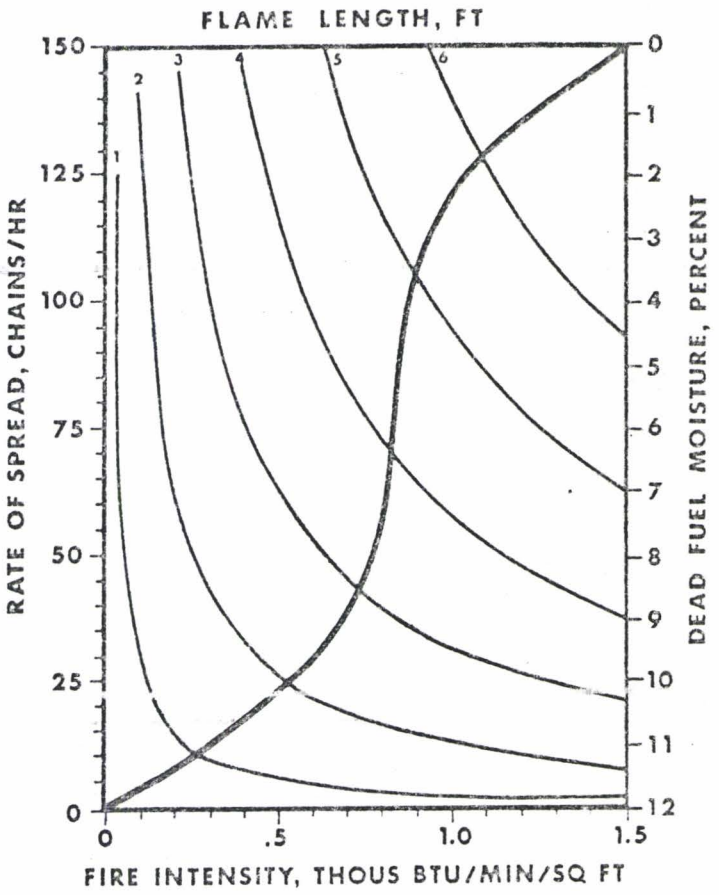
B. CHAPARRAL (6 FT) - HIGH WINDSPEEDS
EXAMPLE 2

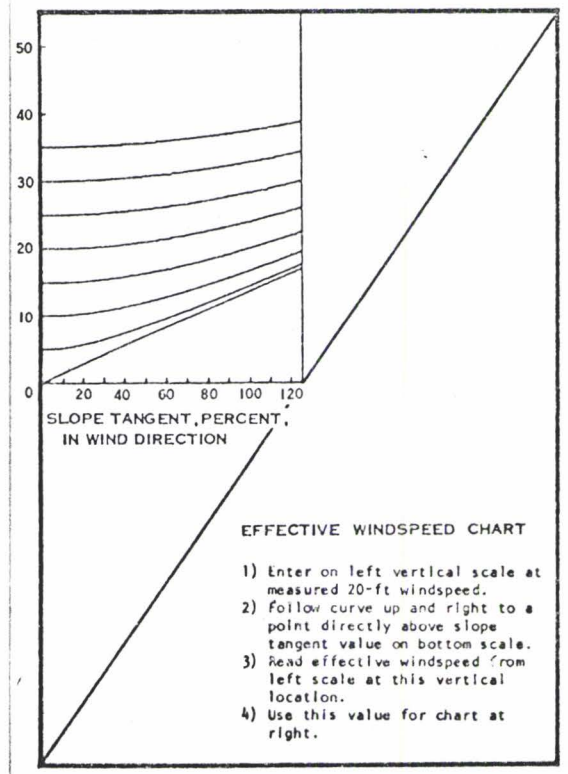

FLAME LENGTH, FT
DEAD FUEL MOISTURE, PERCENT
RATE OF SPREAD, CHAINS/HR
LINE K
LINE D
LINE A
STEP 3a
STEP 3b
STEP 3c
STEP 3d
LIVE FUEL (FOLIAGE) MOISTURE, PERCENT
LIVE FUEL MOISTURE, PERCENT
RATE OF SPREAD
FLAME LENGTH
INTENSITY
FIRE INTENSITY, THOUS BTU/MIN/SQ FT
EFFECTIVE VALUE OF WINDSPEED, MI/HR
SLOPE TANGENT, PERCENT, IN WIND DIRECTION
EFFECTIVE WINDSPEED CHART
1) Enter on left vertical scale at measured 20-ft windspeed.
2) Follow curve up and right to a point directly above slope tangent value on bottom scale.
3) Read effective windspeed from left scale at this vertical location.
4) Use this value for chart at right.
NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR

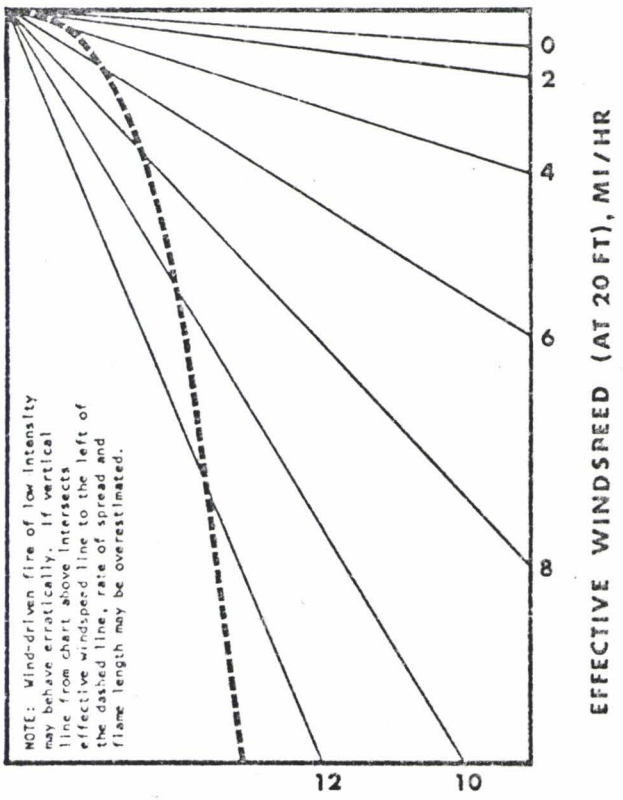
N O M O G R A P H S

A. SHORT GRASS (1 FT) -LOW WINDSPEEDS

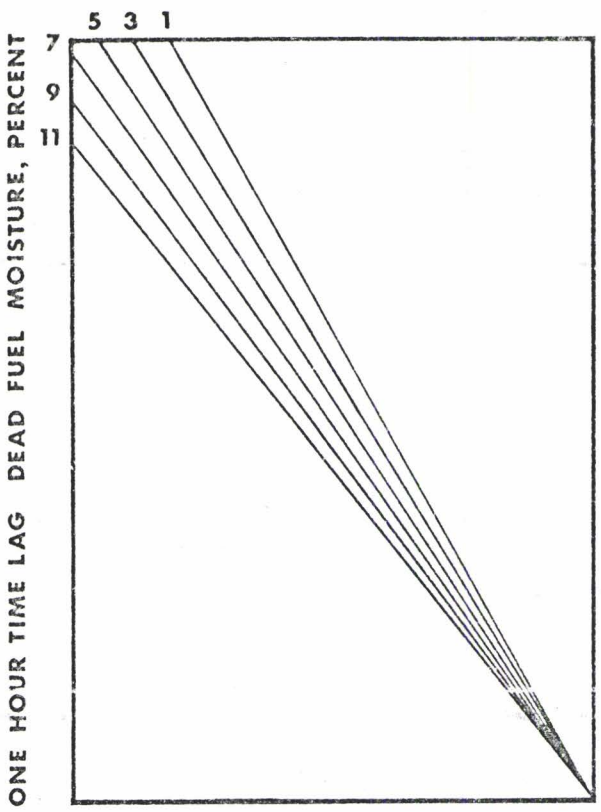


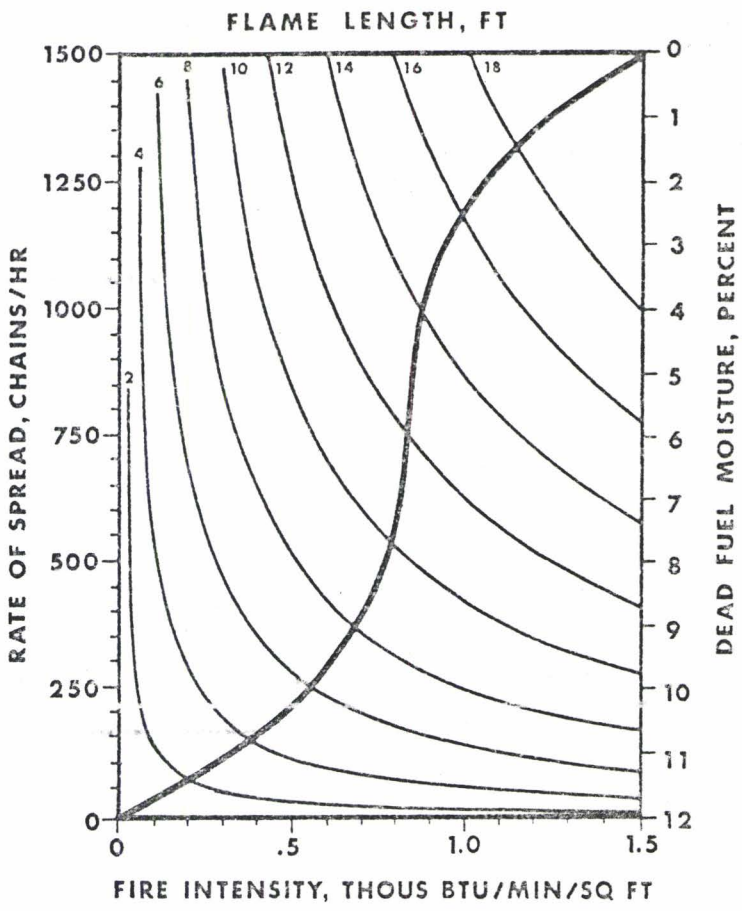


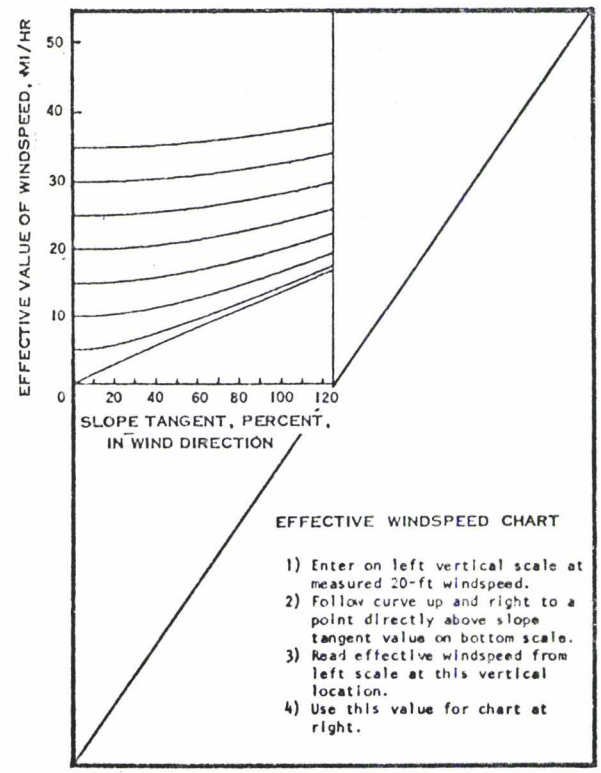

50
40
30
20
10
0
20 40 60 80 100 120
SLOPE TANGENT, PERCENT, IN WIND DIRECTION
EFFECTIVE WINDSPEED CHART
1) Enter on left vertical scale at measured 20-ft windspeed.
2) Follow curve up and right to a point directly above slope tangent value on bottom scale.
3) Read effective windspeed from left scale at this vertical location.
4) Use this value for chart at right.

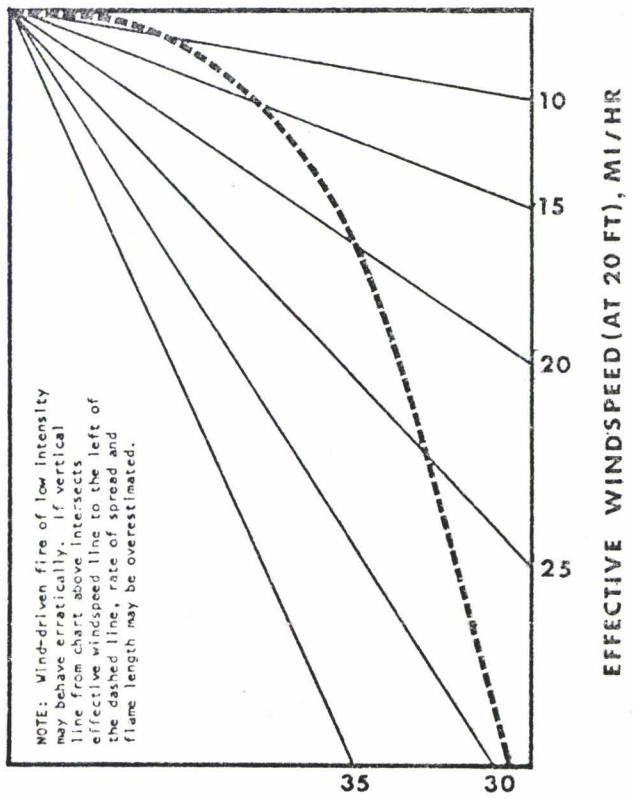

NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
0
2
4
6
8
12
10
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR

A. SHORT GRASS(1 FT) - HIGH WINDSPEEDS

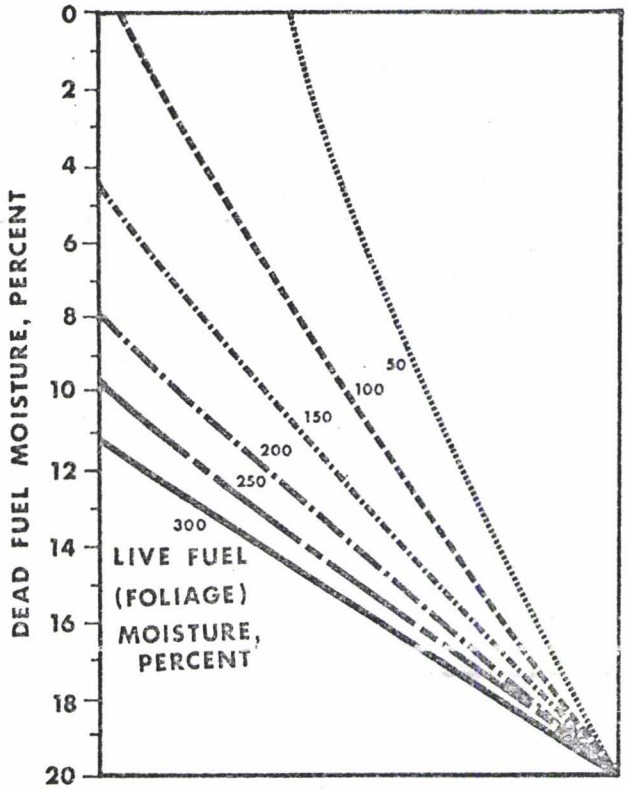


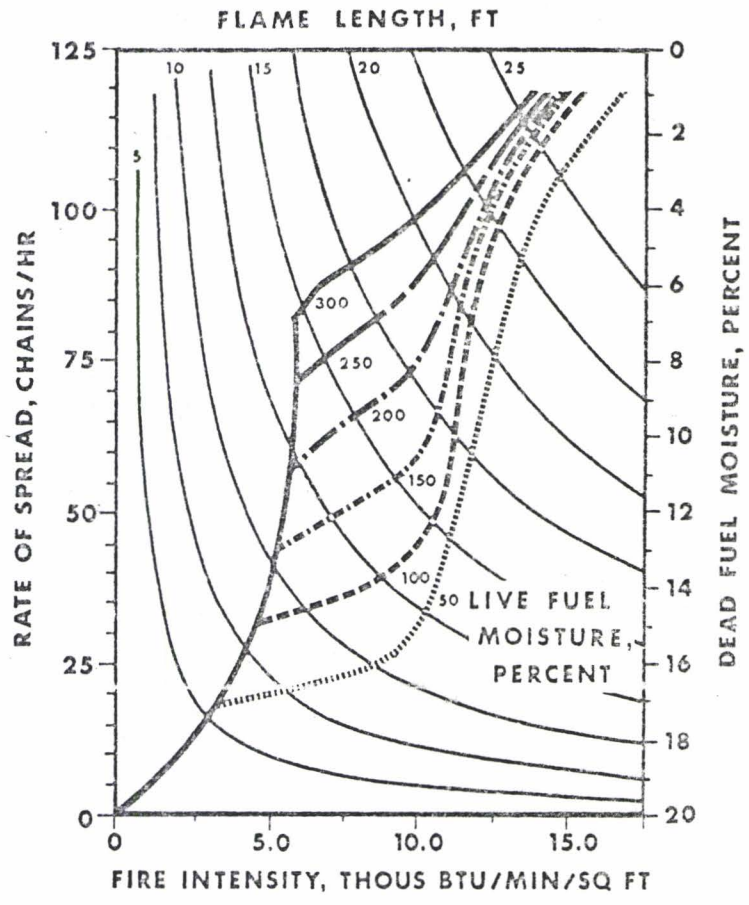


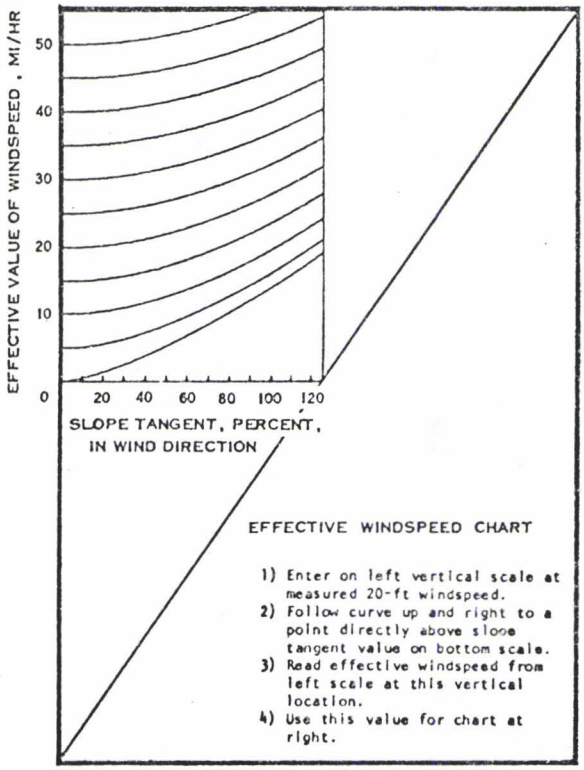


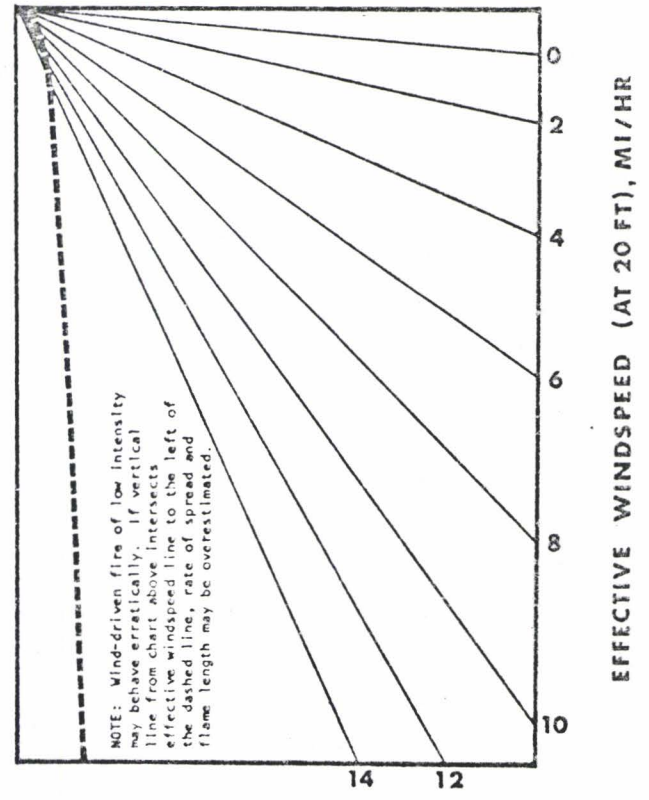

NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
10
15
20
25
35
30
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR

B. CHAPARRAL (6 FT) - LOW WINDSPEEDS

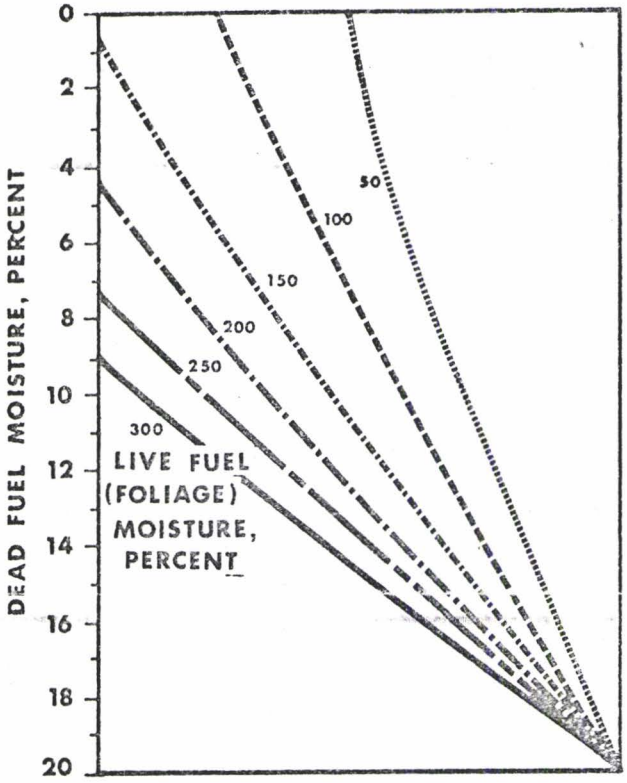


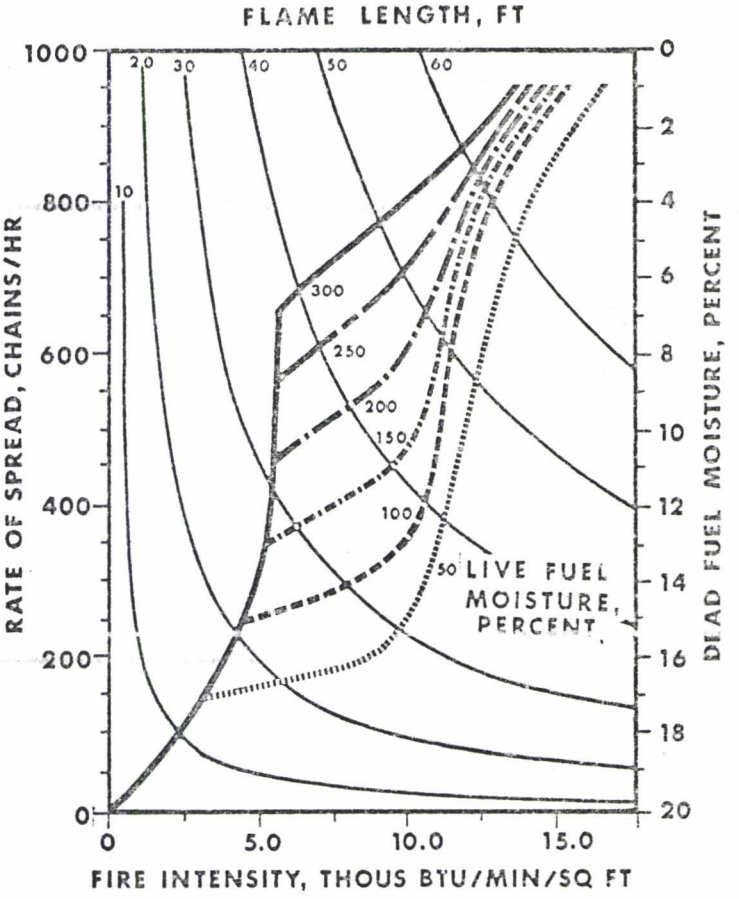


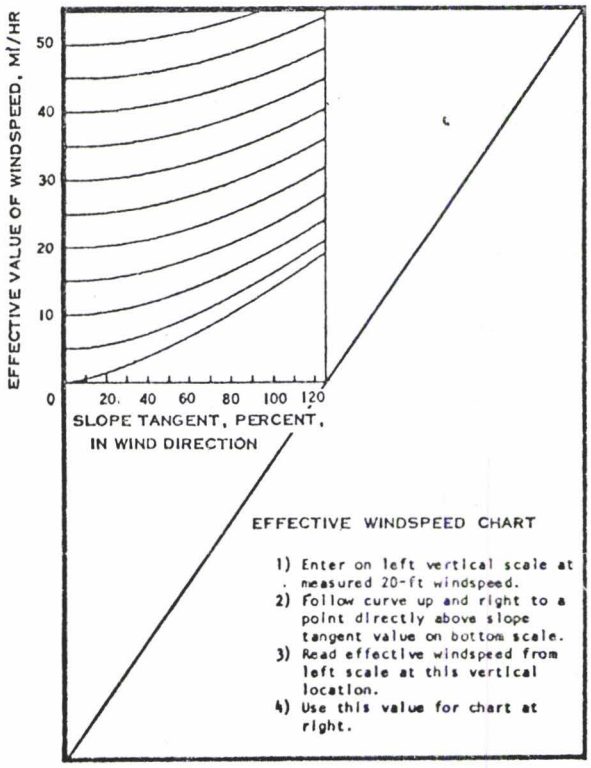


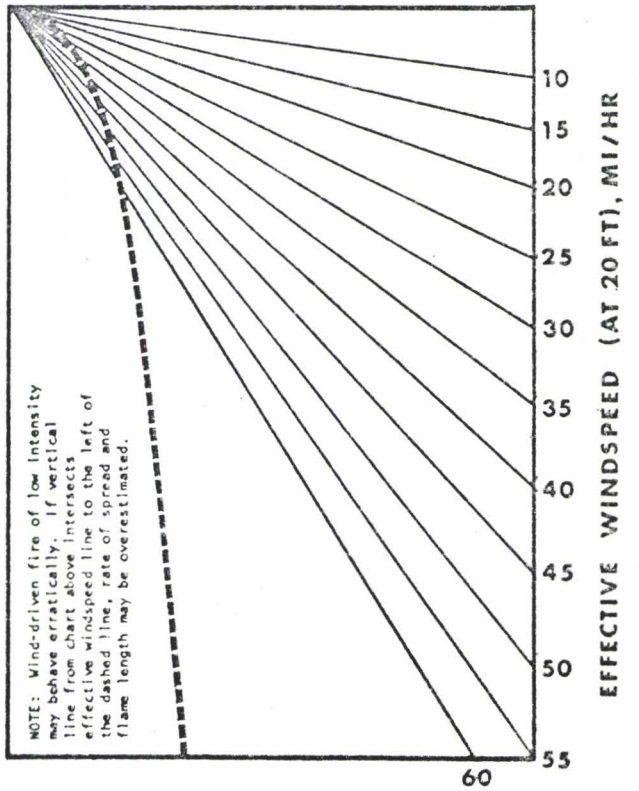

NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
0
2
4
6
8
10
14
12
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR

B. CHAPARRAL (6 FT)- HIGH WINDSPEEDS

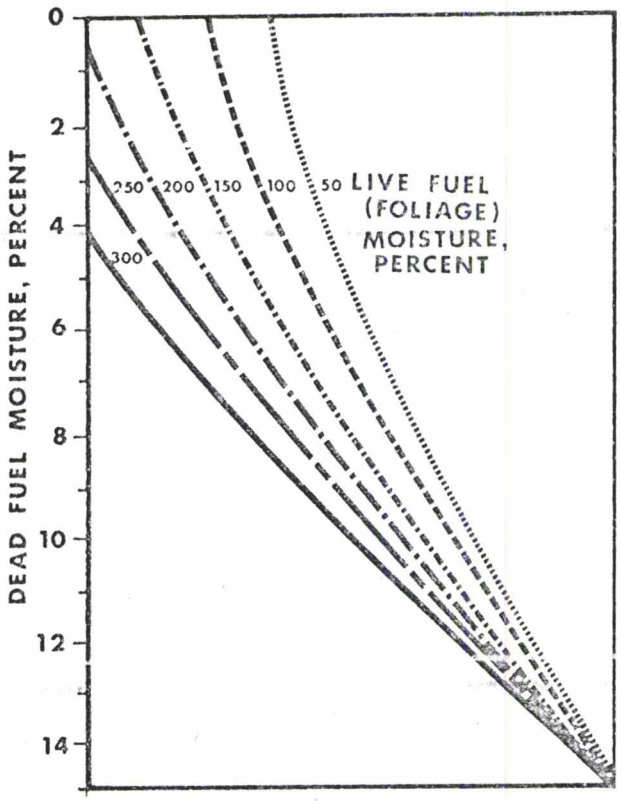


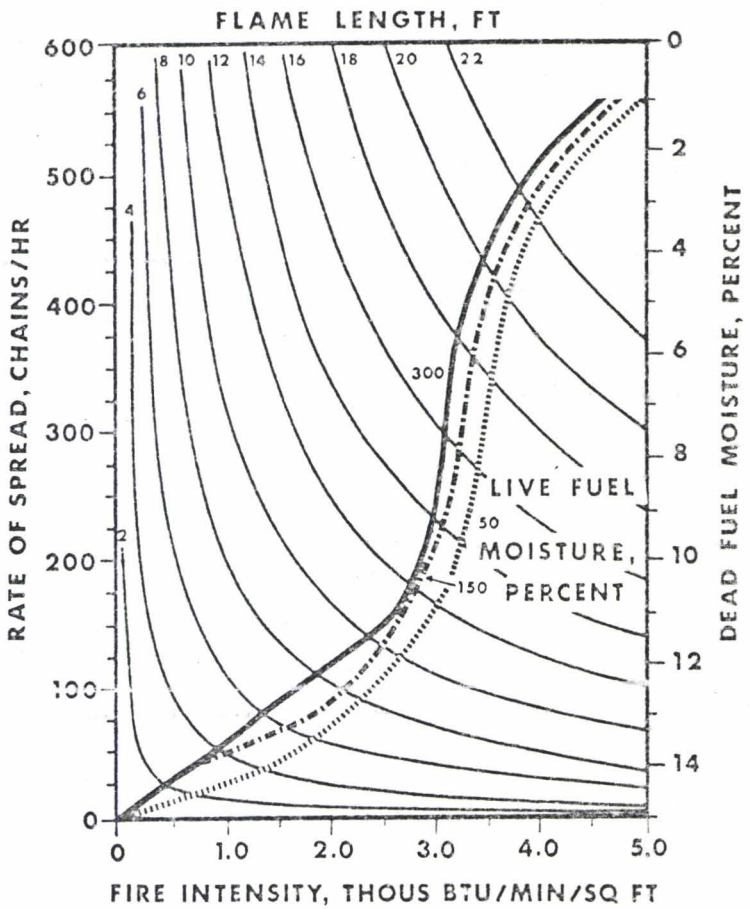


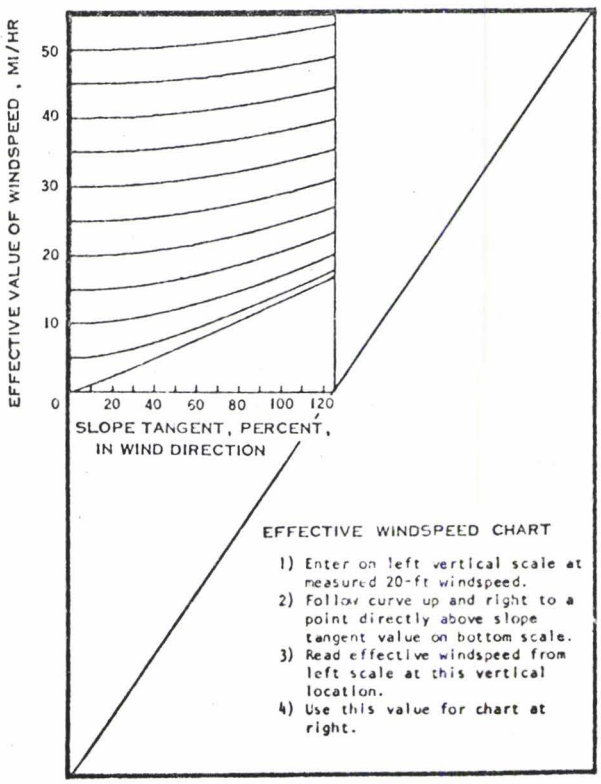


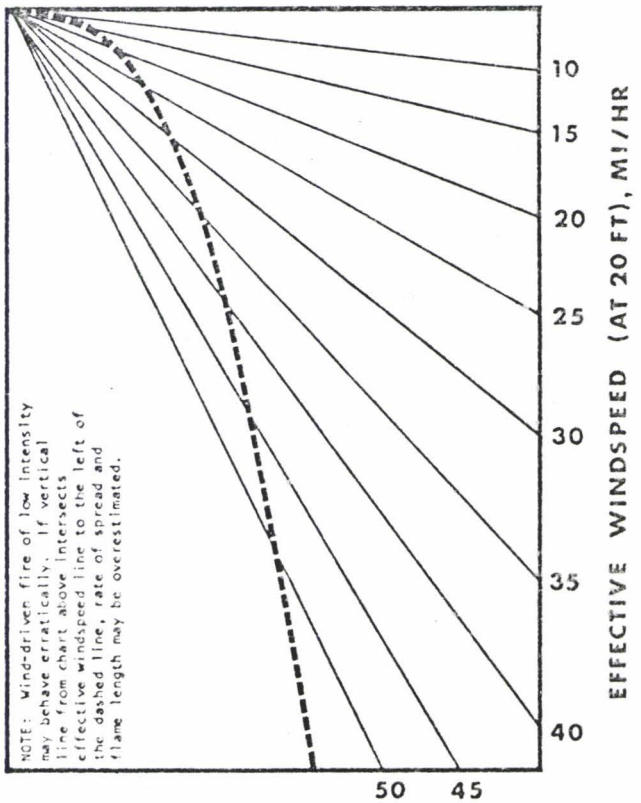

NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR
10
15
20
25
30
35
40
45
50
55
60

C. TIMBER (GRASS & UNDERSTORY) - HIGH WINDSPEEDS

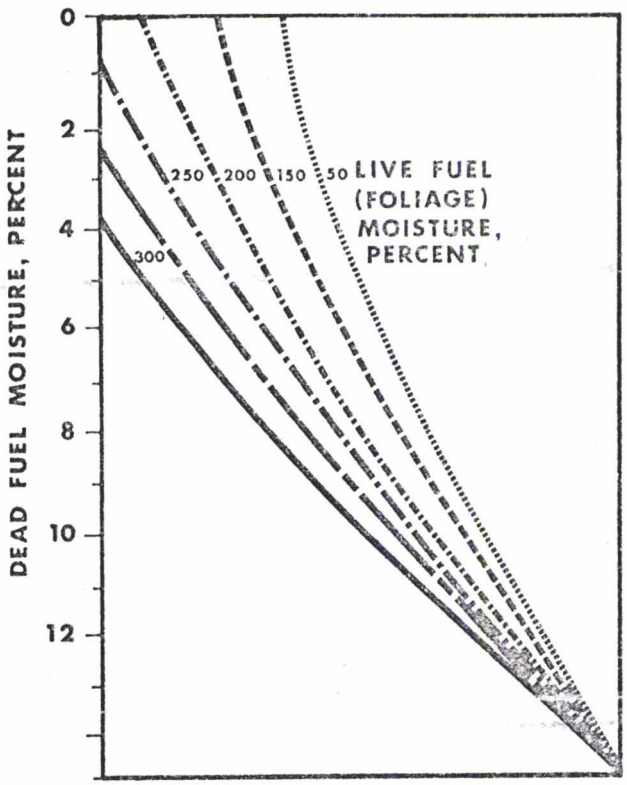


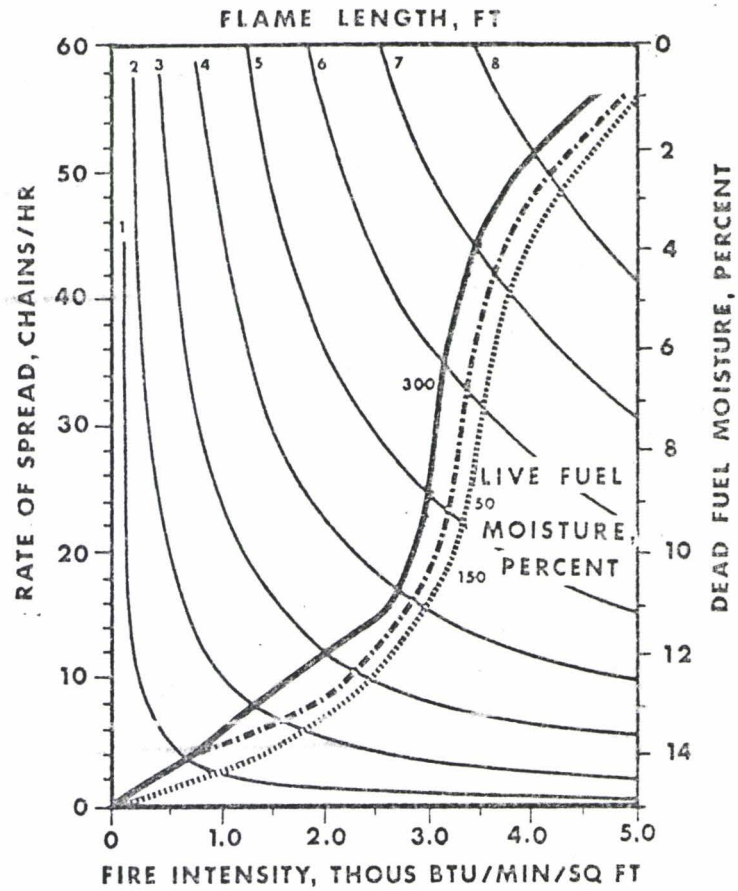


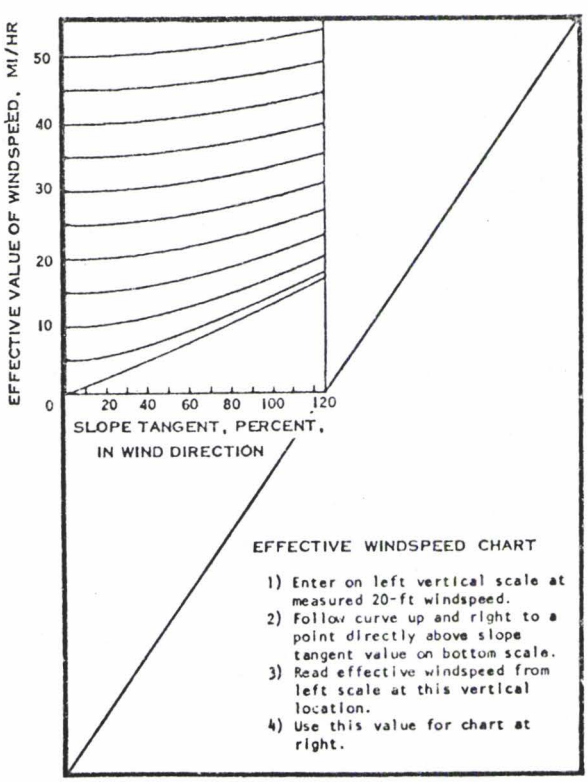


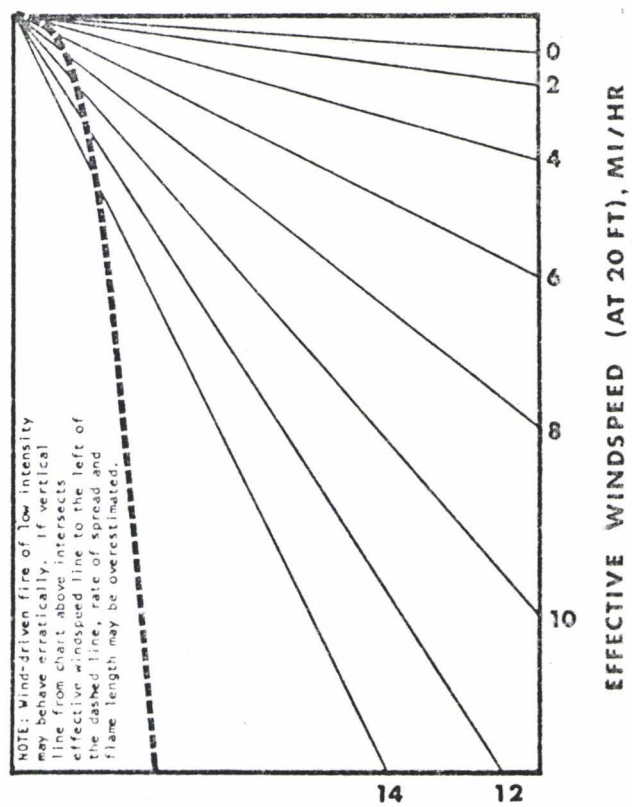

NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR
10
15
20
25
30
35
40
50
45

C. TIMBER (GRASS & UNDERSTORY) - LOW WINDSPEEDS

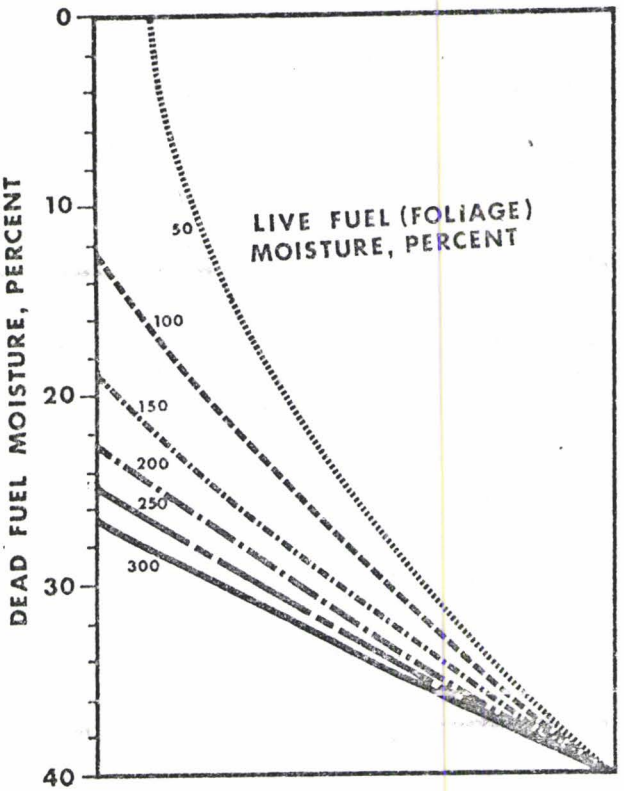


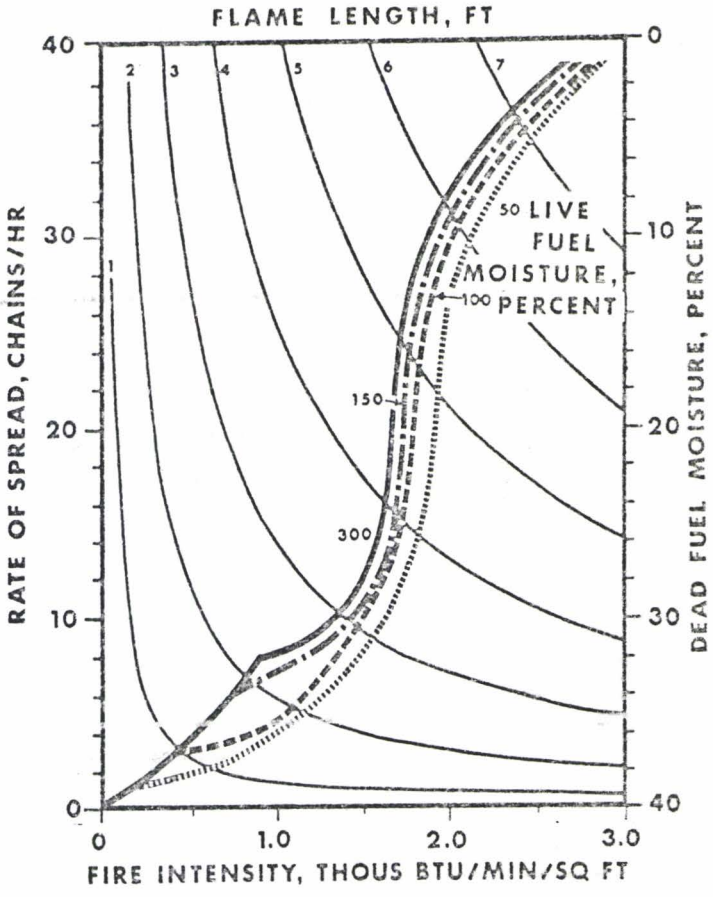


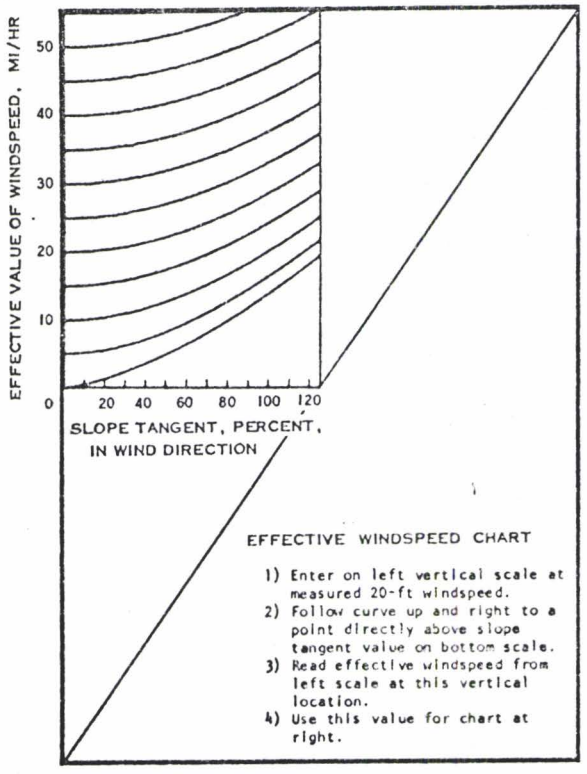


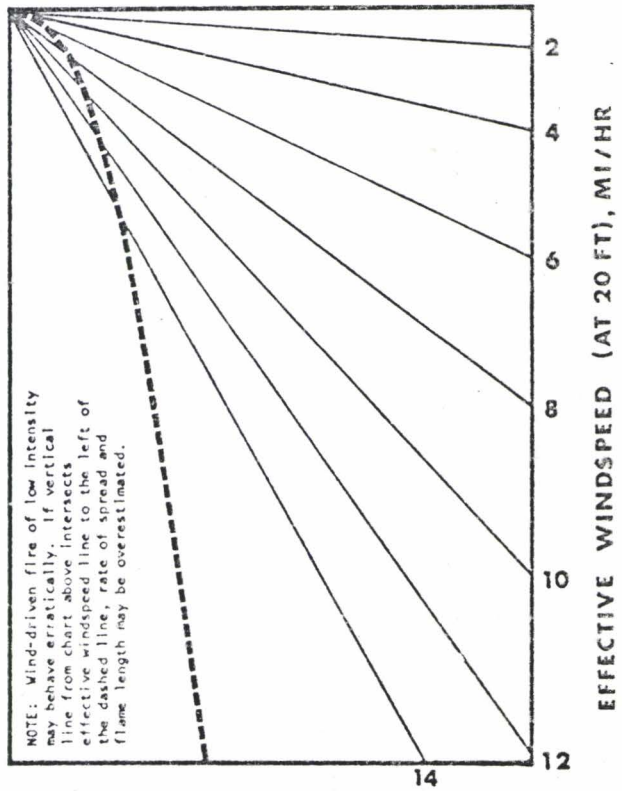

NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
14
12
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR
0
2
4
6
8
10

D. EASILY BURNED MIXED COVER - LOW WINDSPEEDS

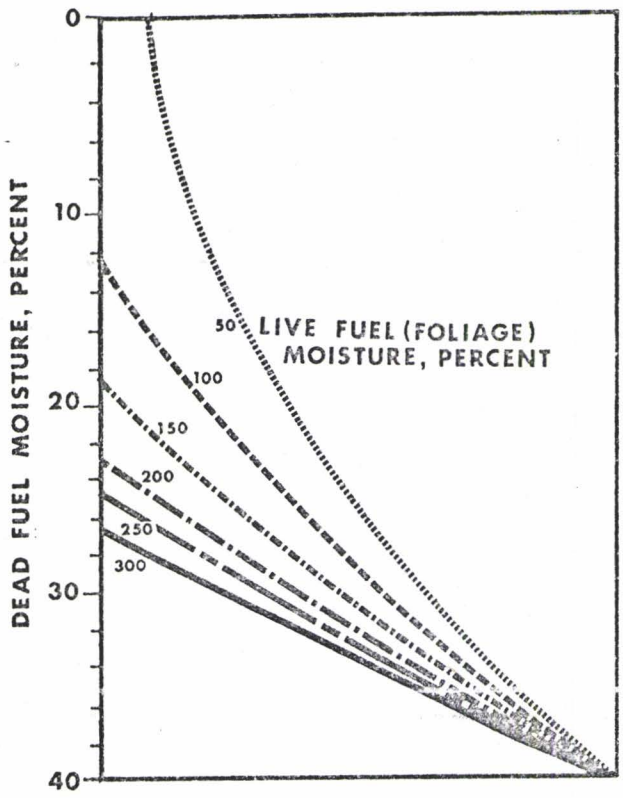


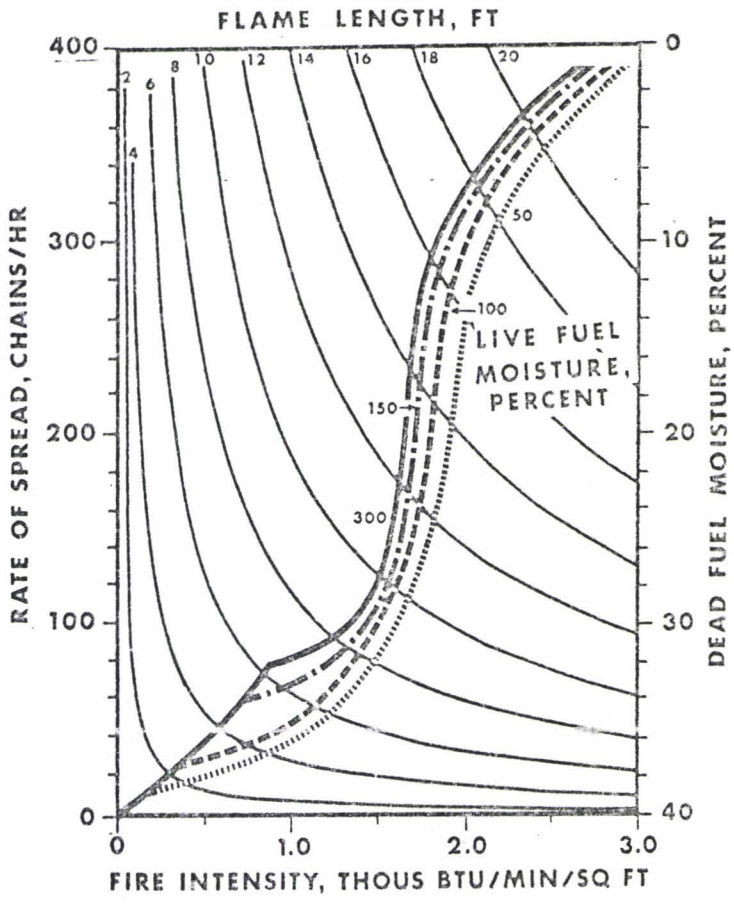


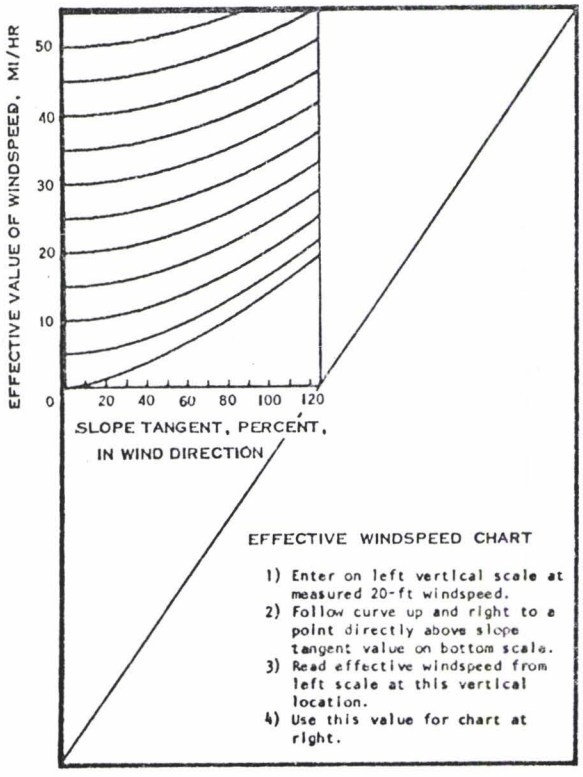


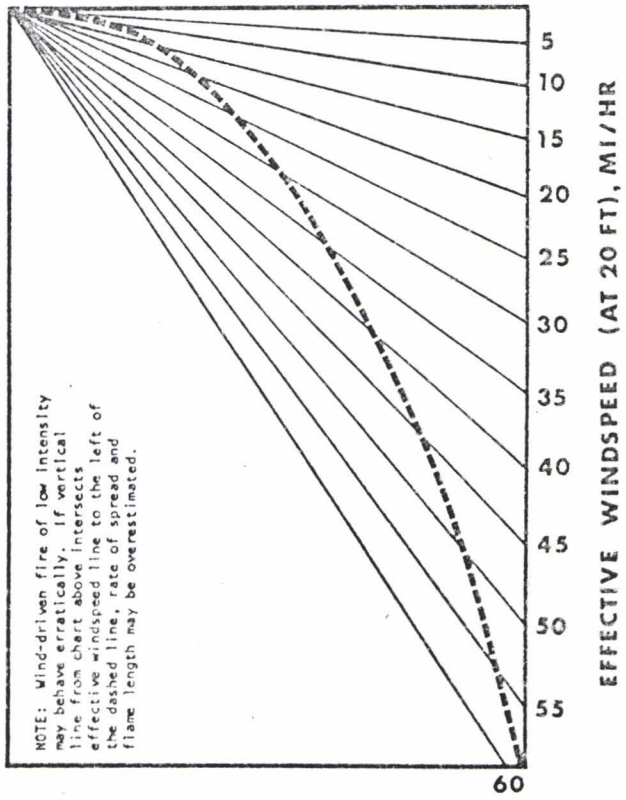

NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR
2
4
6
8
10
12

D. EASILY BURNED MIXED COVER-HIGH WINDSPEEDS

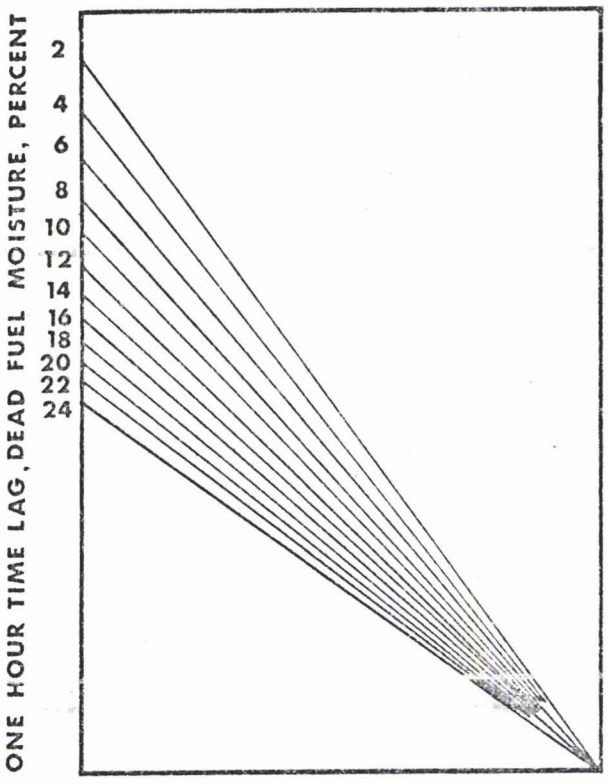


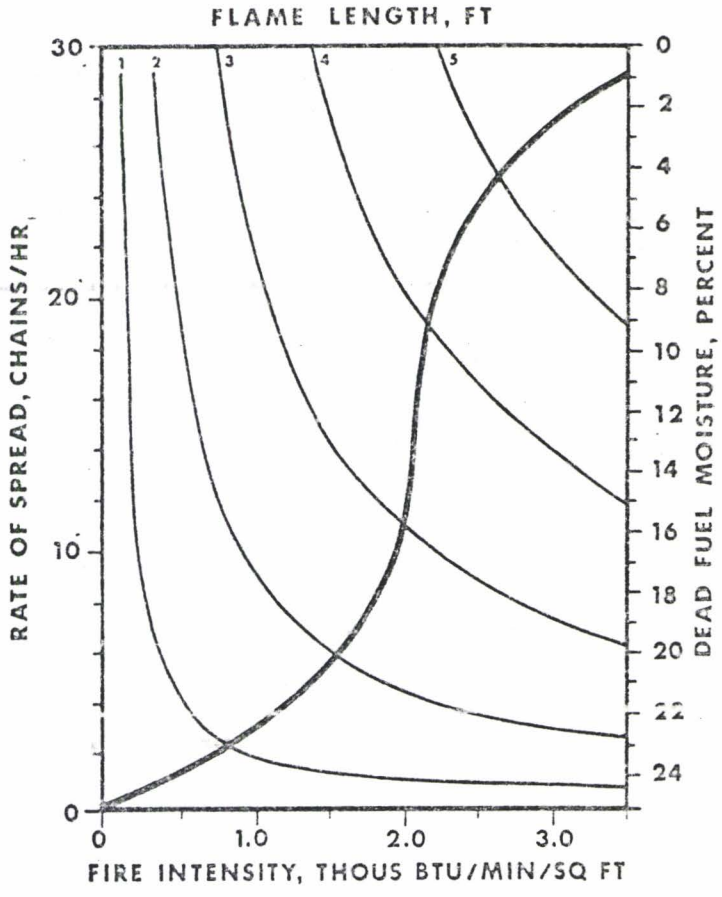


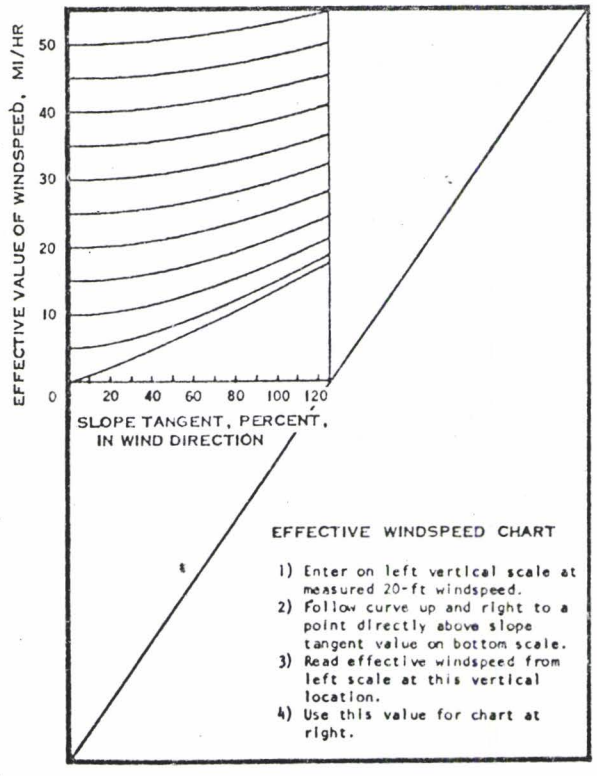


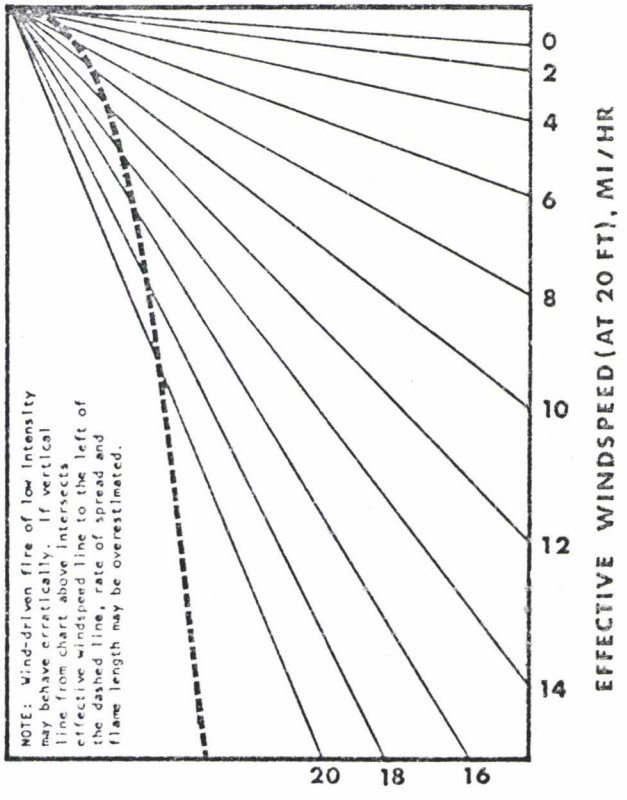


E. HARDWOOD LITTER - LOW WINDSPEEDS

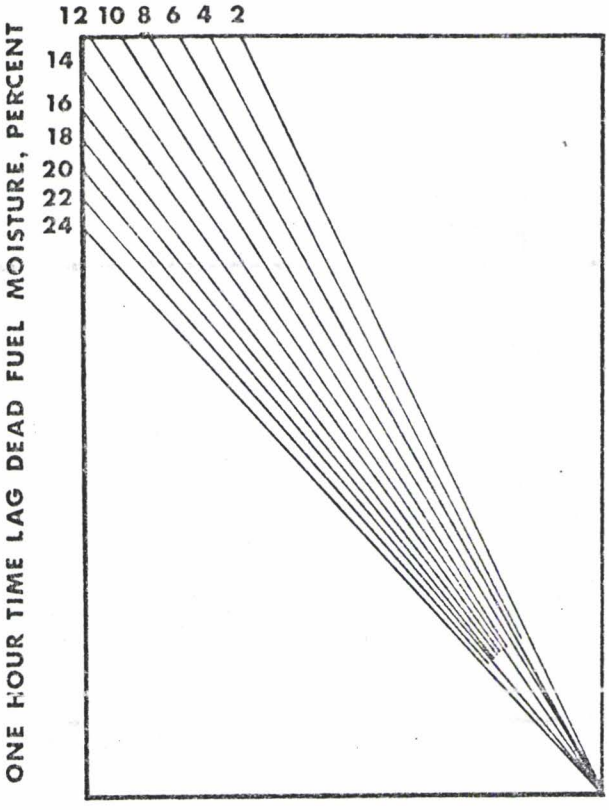


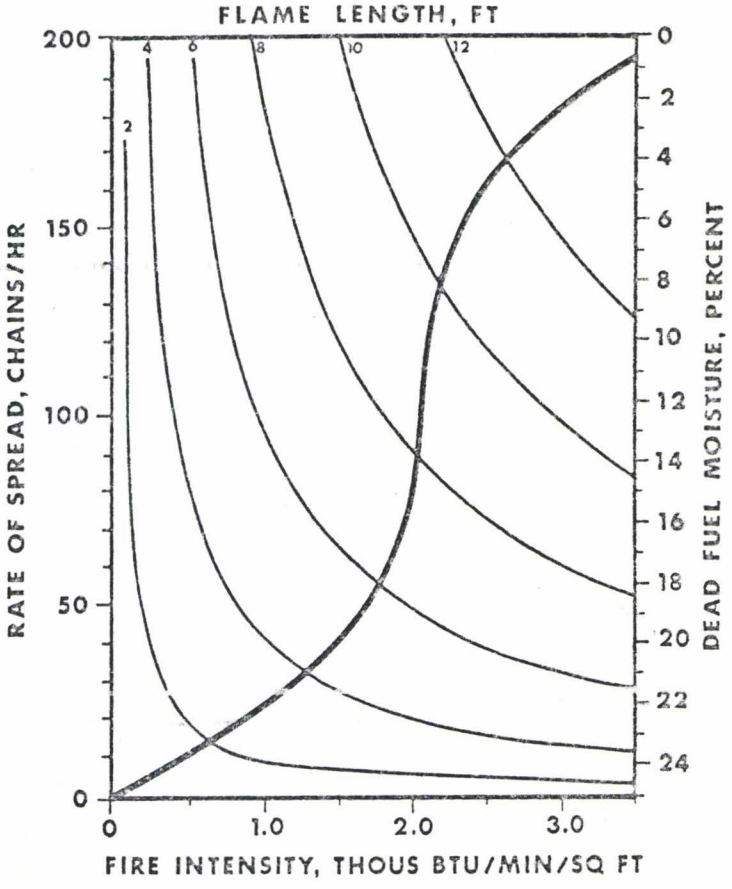


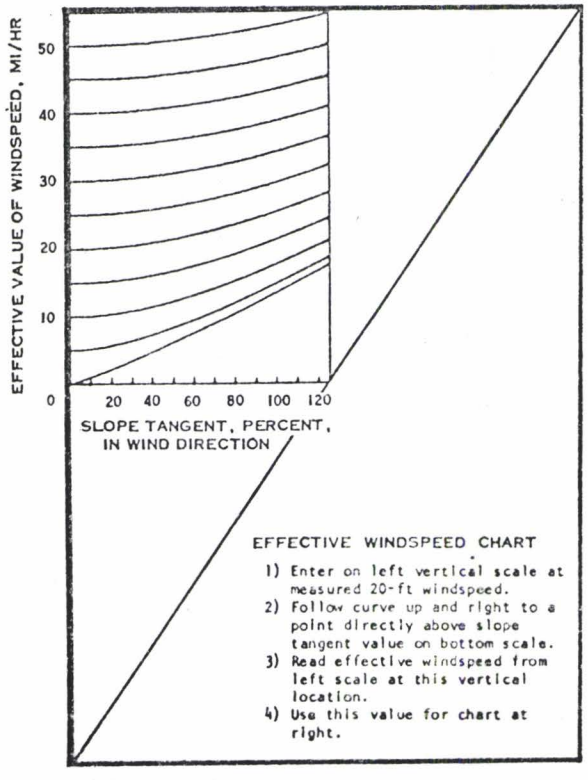


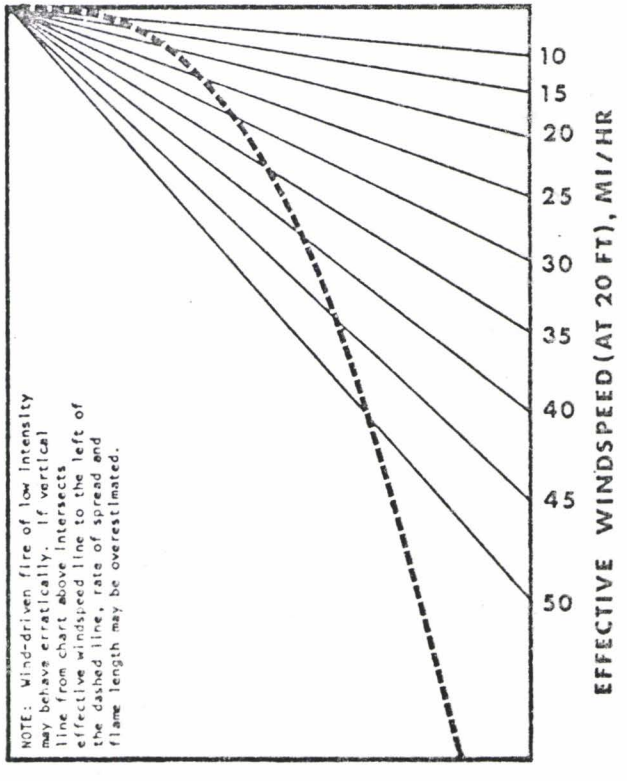

NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR
0
2
4
6
8
10
12
14
20
18
16

E. HARDWOOD LITTER - HIGH WINDSPEEDS

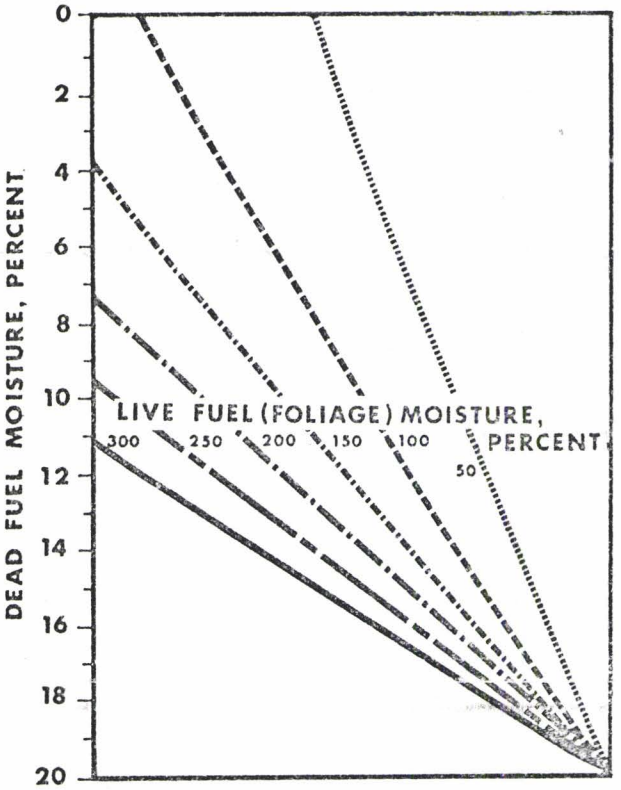


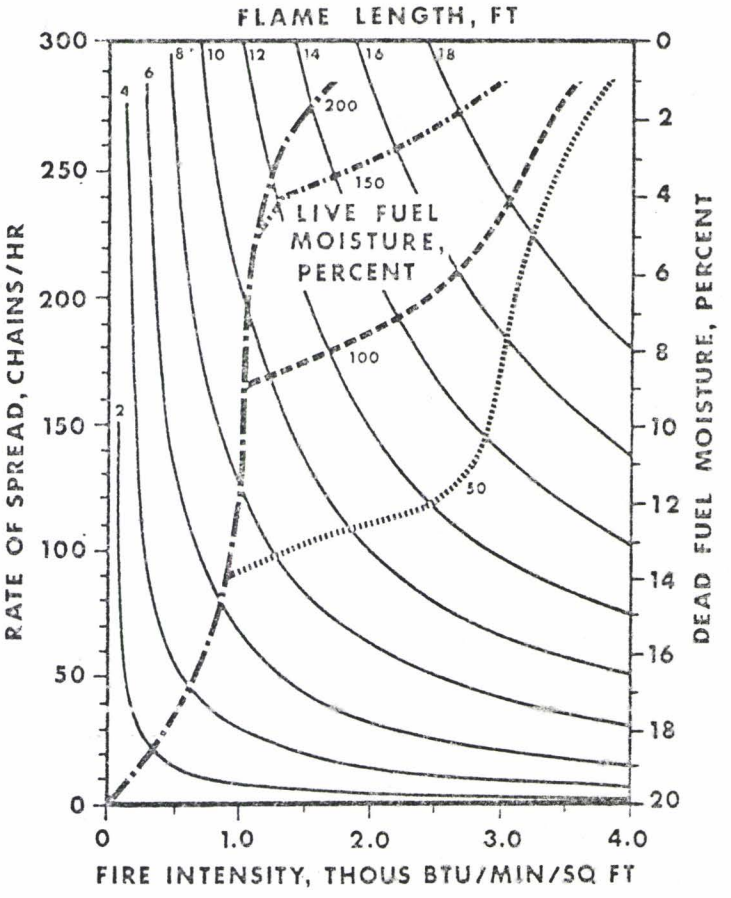


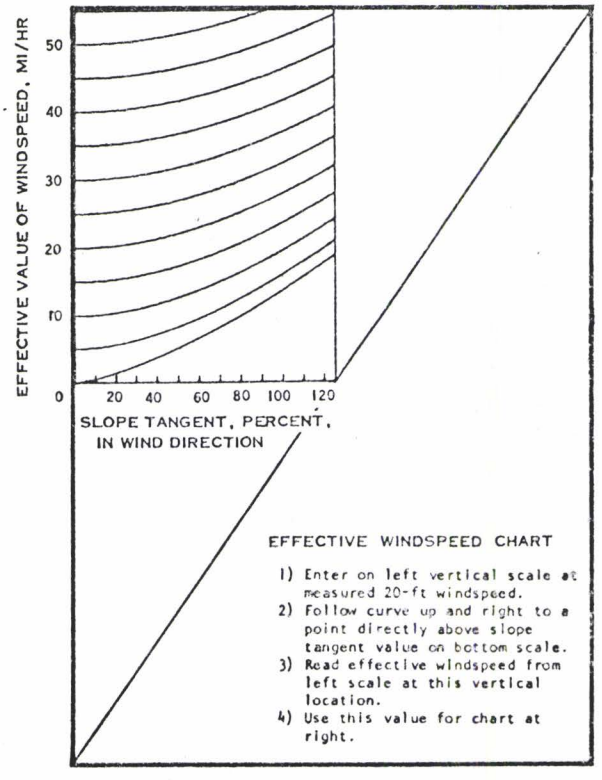


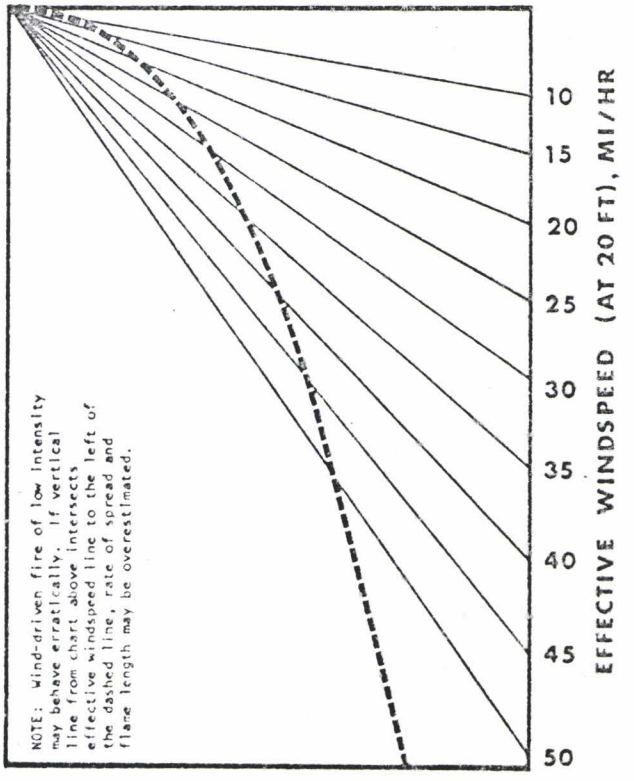

10
15
20
25
30
35
40
45
50
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR
NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.

F. BRUSH (2 FT) - HIGH WINDSPEEDS

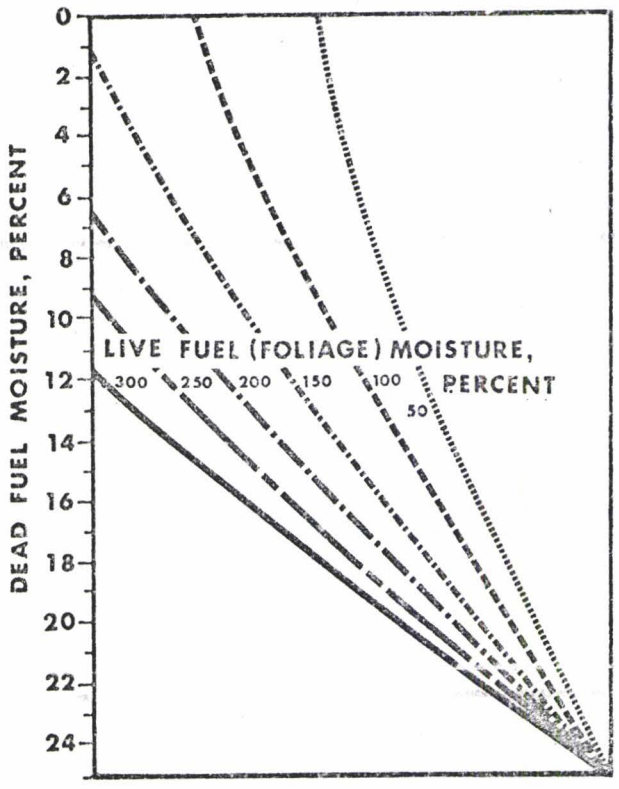


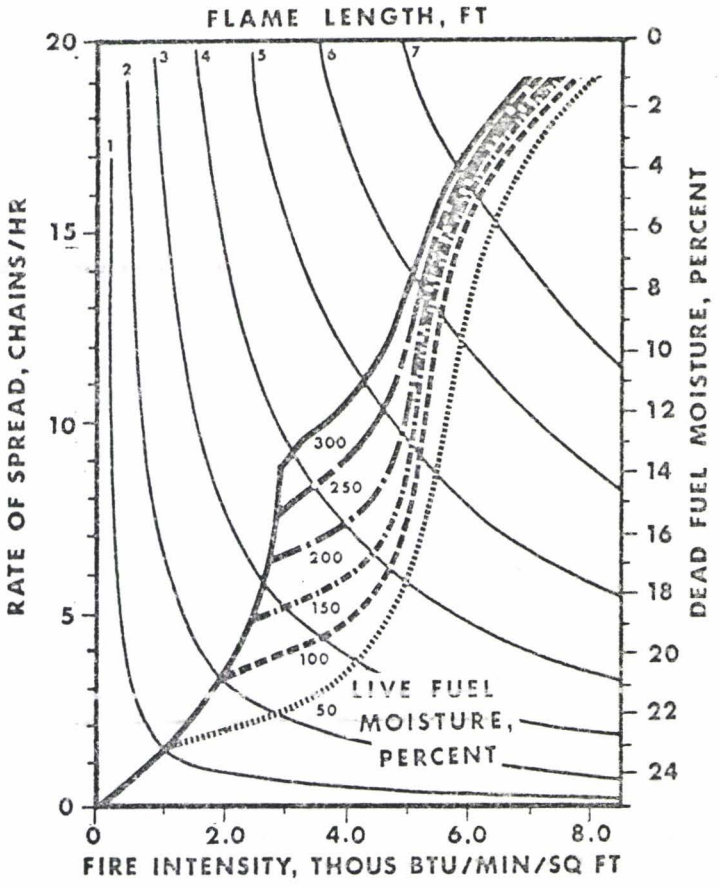


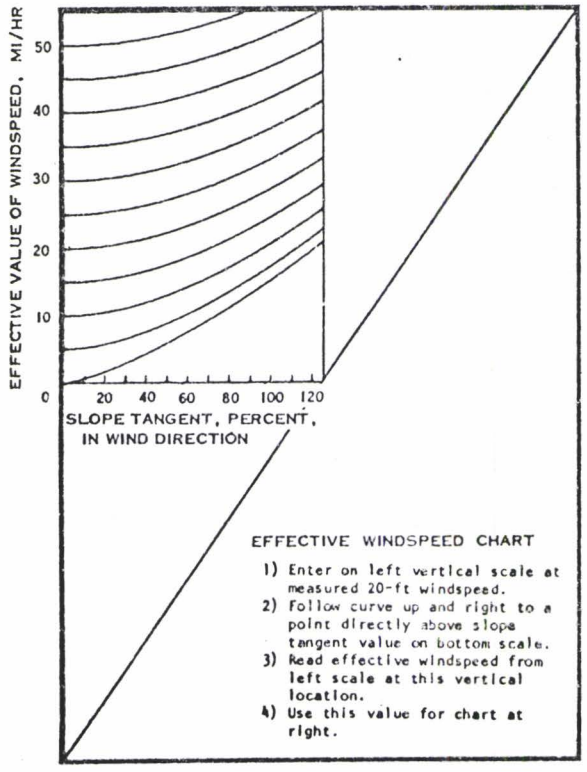


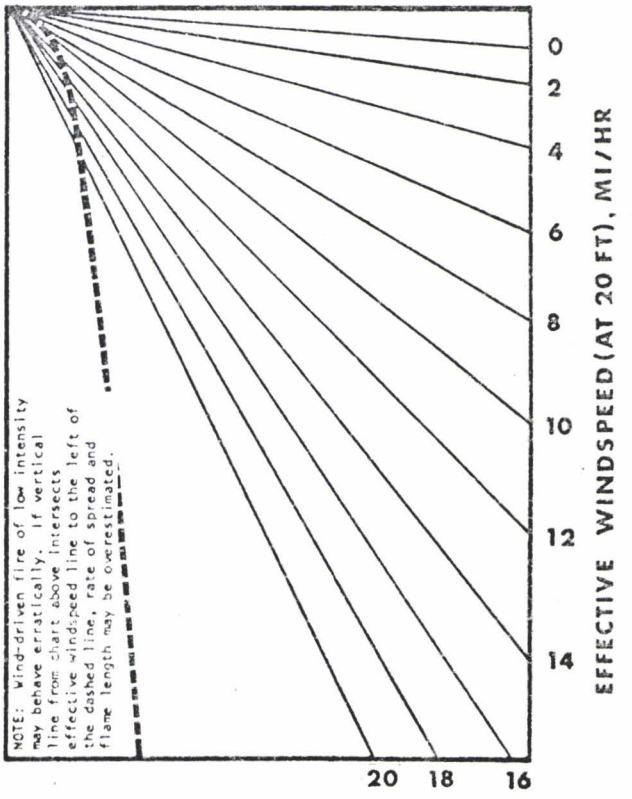

NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR
10
15
20
25
30
35
40
45
50

G. TIMBER (LITTER & UNDERSTORY) - LOW WINDSPEEDS

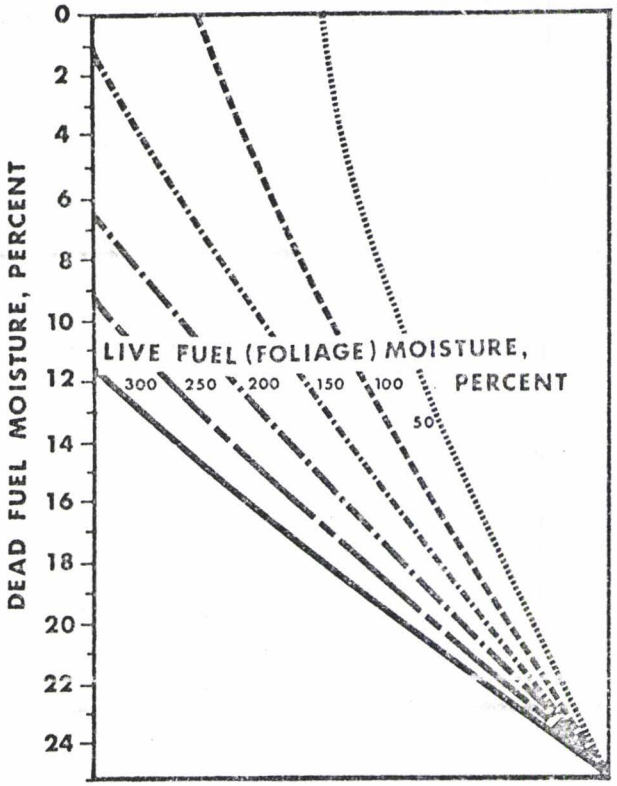


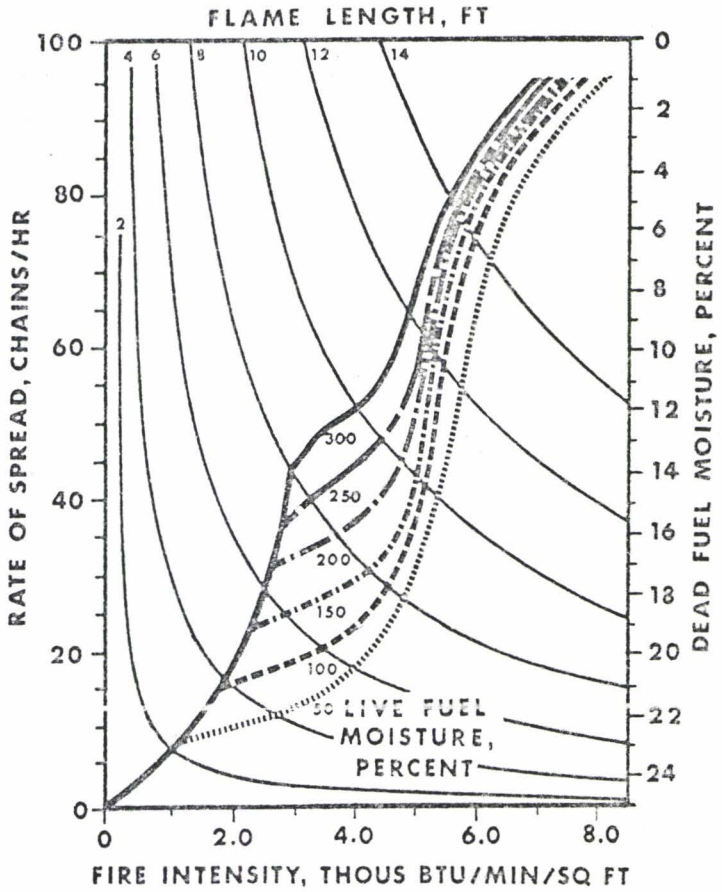


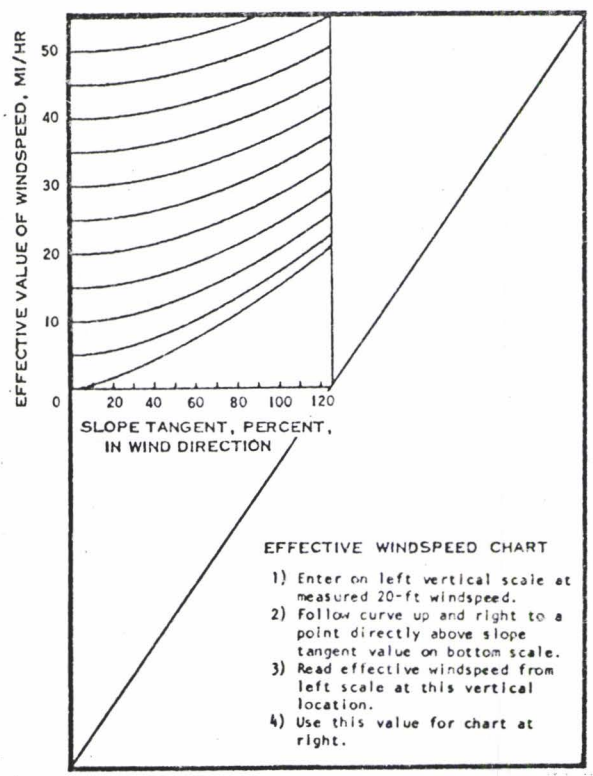


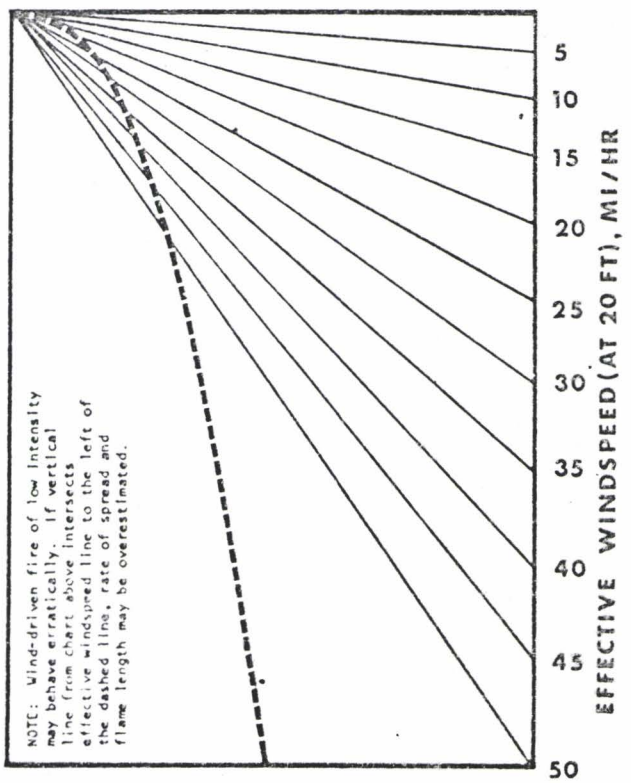

NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR
0
2
4
6
8
10
12
14
20
18
16

G. TIMBER (LITTER & UNDERSTORY)-HIGH WINDSPEEDS

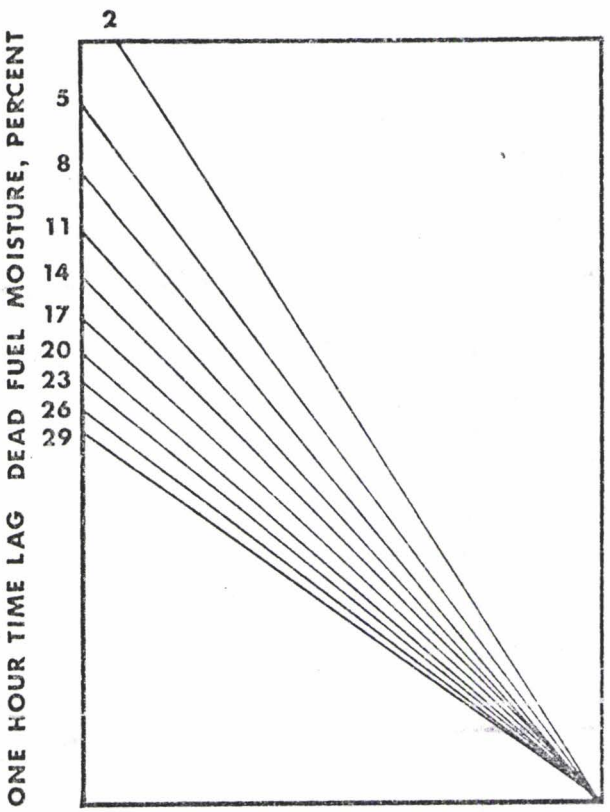


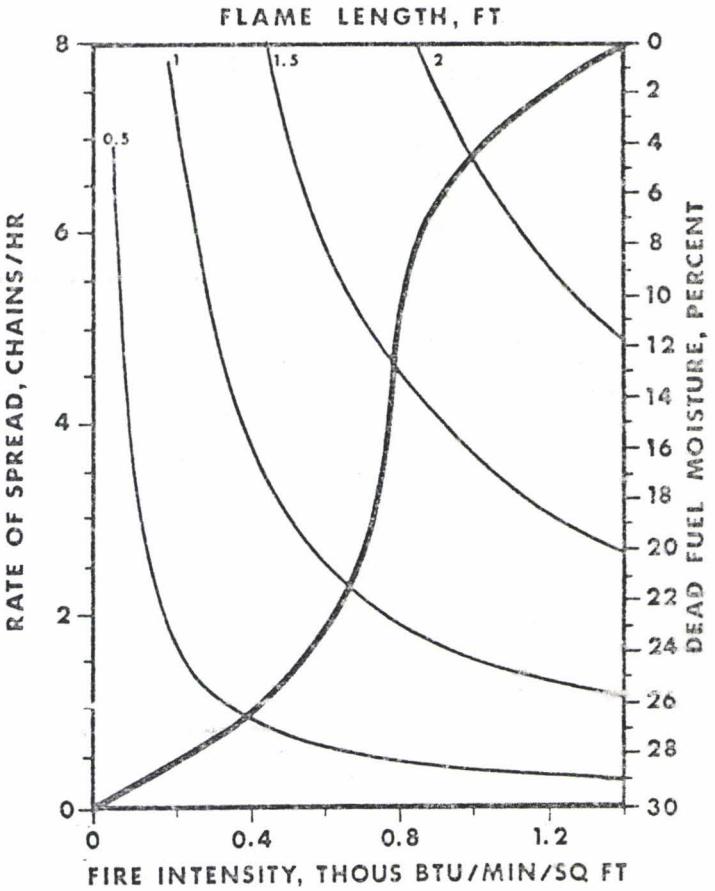


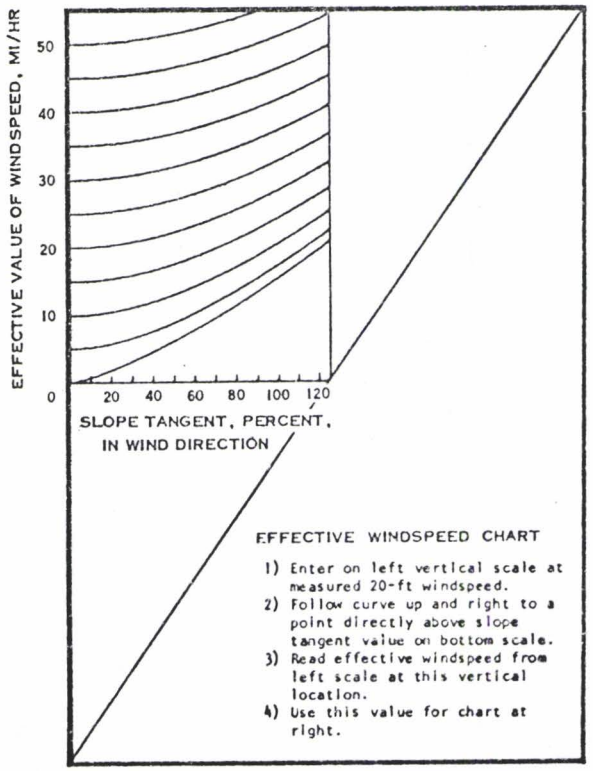


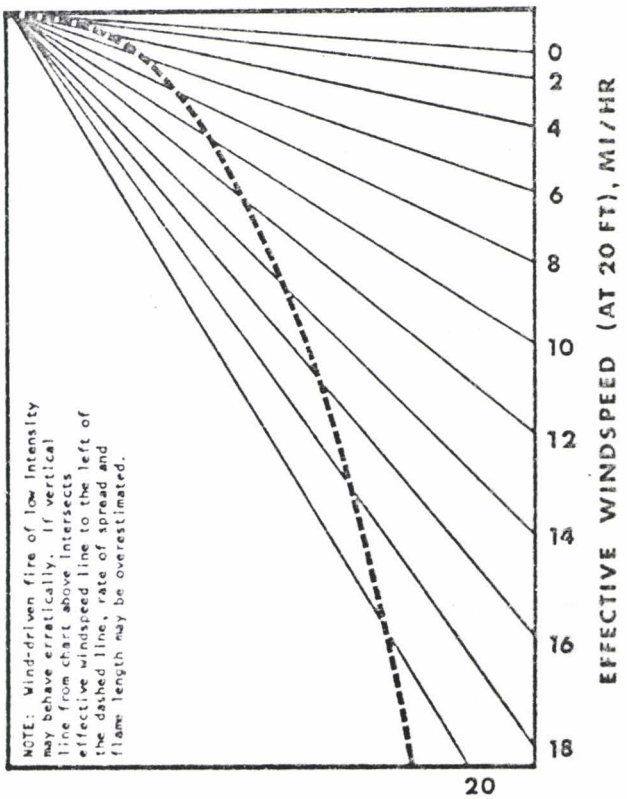

NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR
5
10
15
20
25
30
35
40
45
50

H. CLOSED TIMBER LITTER - LOW WINDSPEEDS

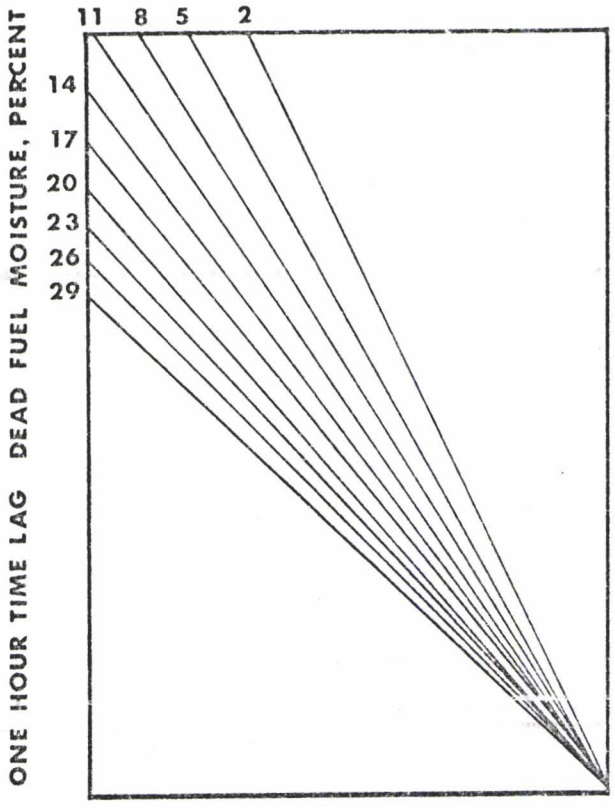


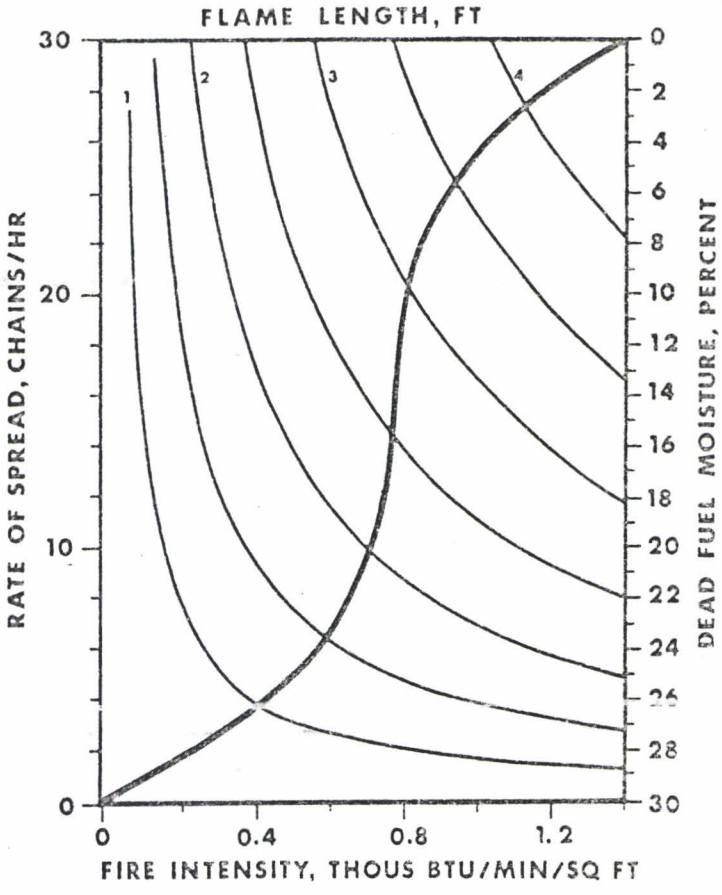


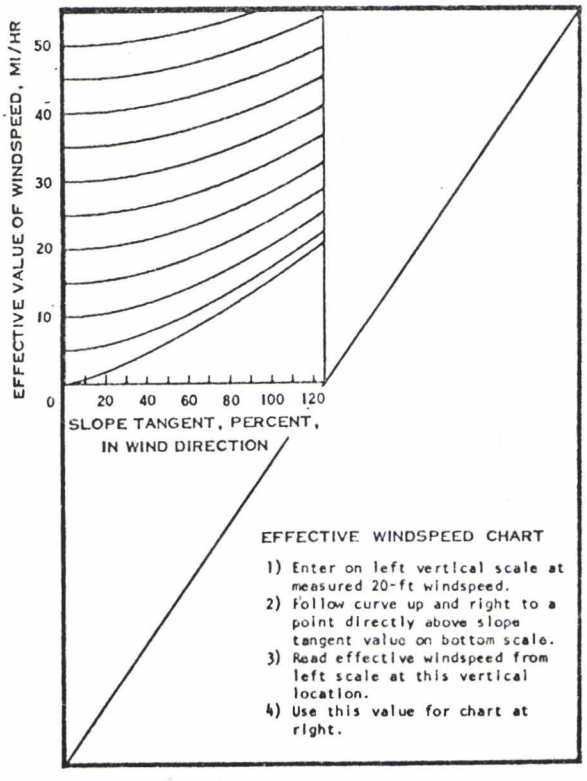


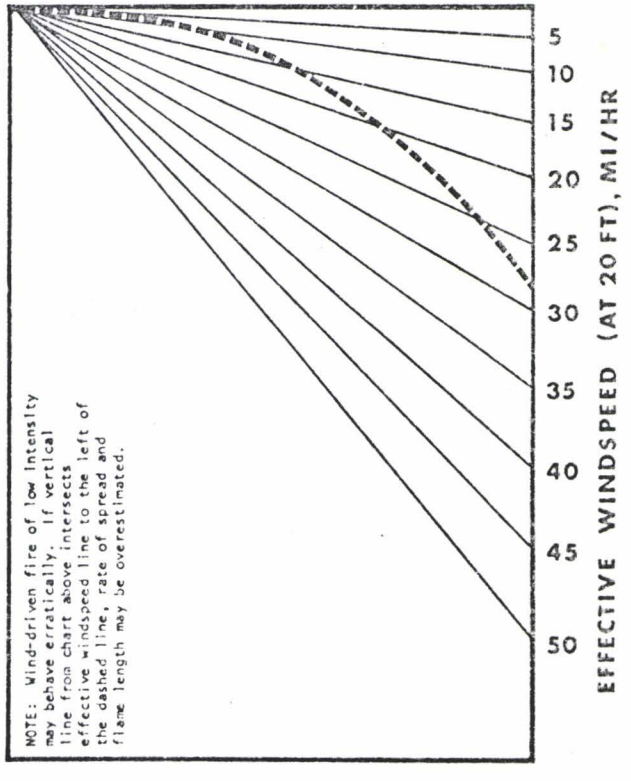

NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR
0
2
4
6
8
10
12
14
16
18

H. CLOSED TIMBER LITTER - HIGH WINDSPEEDS

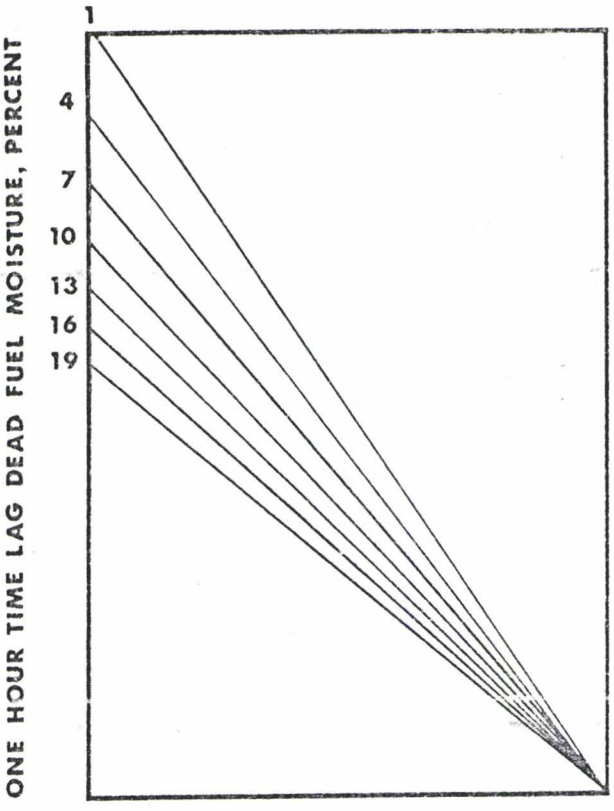


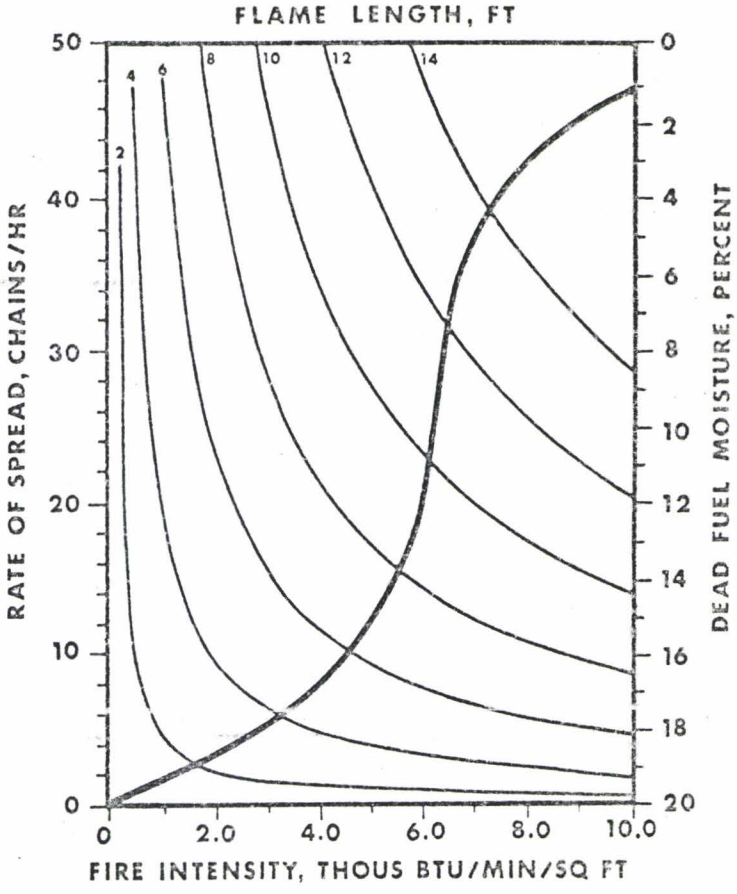


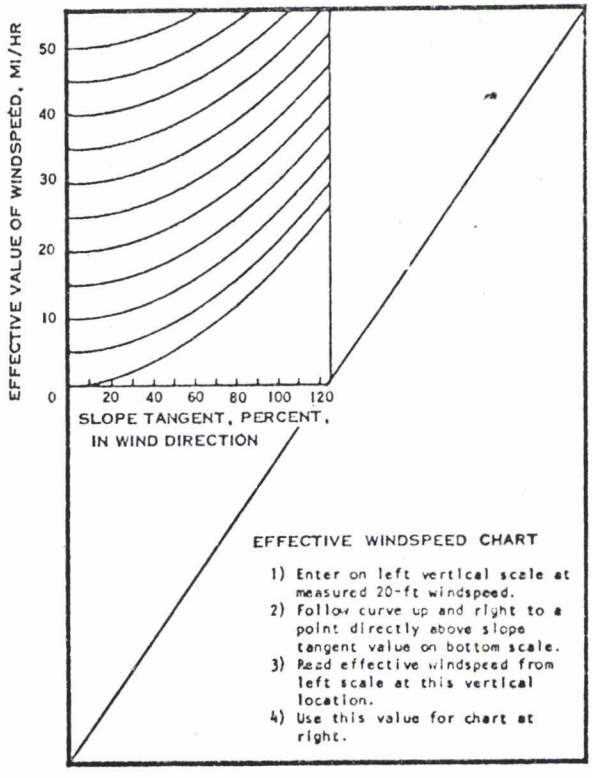

EFFECTIVE VALUE OF WINDSPEED, MI/HR
0 10 20 30 40 50
20 40 60 80 100 120
SLOPE TANGENT, PERCENT, IN WIND DIRECTION
EFFECTIVE WINDSPEED CHART
1) Enter on left vertical scale at measured 20-ft windspeed.
2) Follow curve up and right to a point directly above slope tangent value on bottom scale.
3) Read effective windspeed from left scale at this vertical location.
4) Use this value for chart at right.

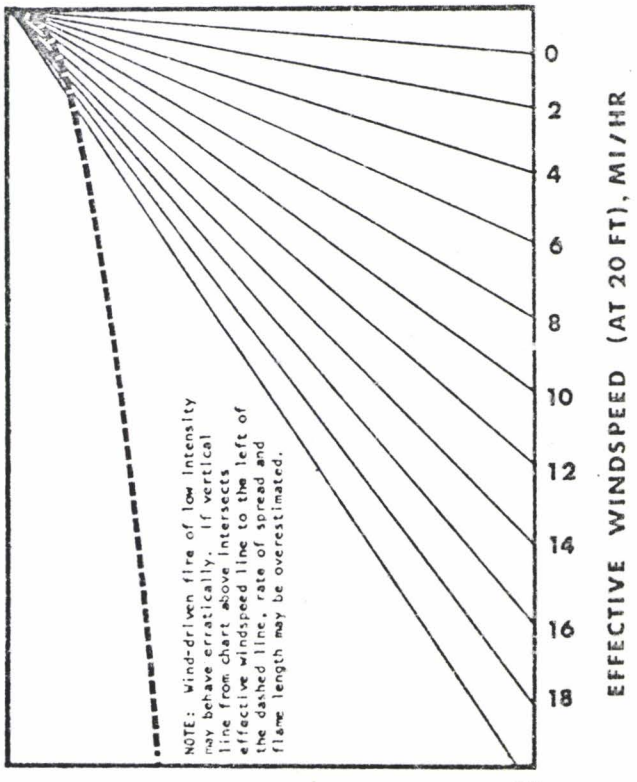

NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR
5 10 15 20 25 30 35 40 45 50

I. MEDIUM LOGGING SLASH - LOW WINDSPEEDS

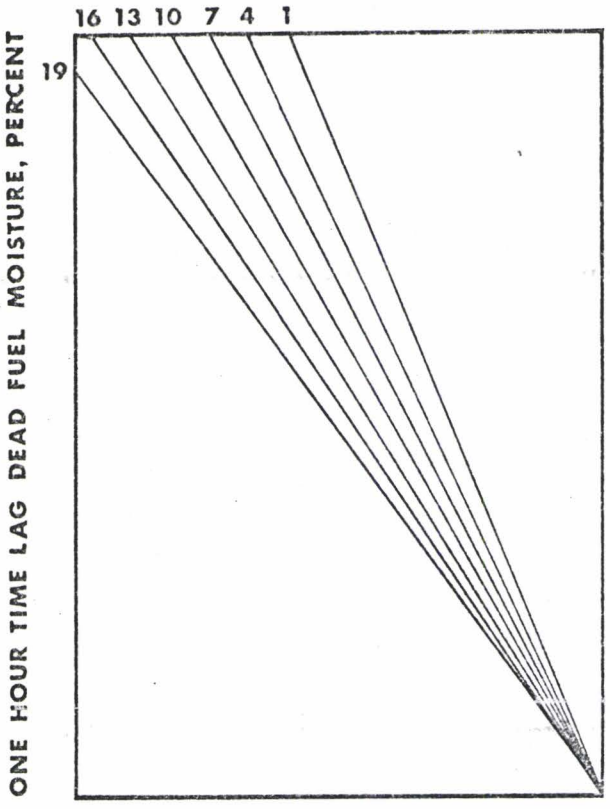


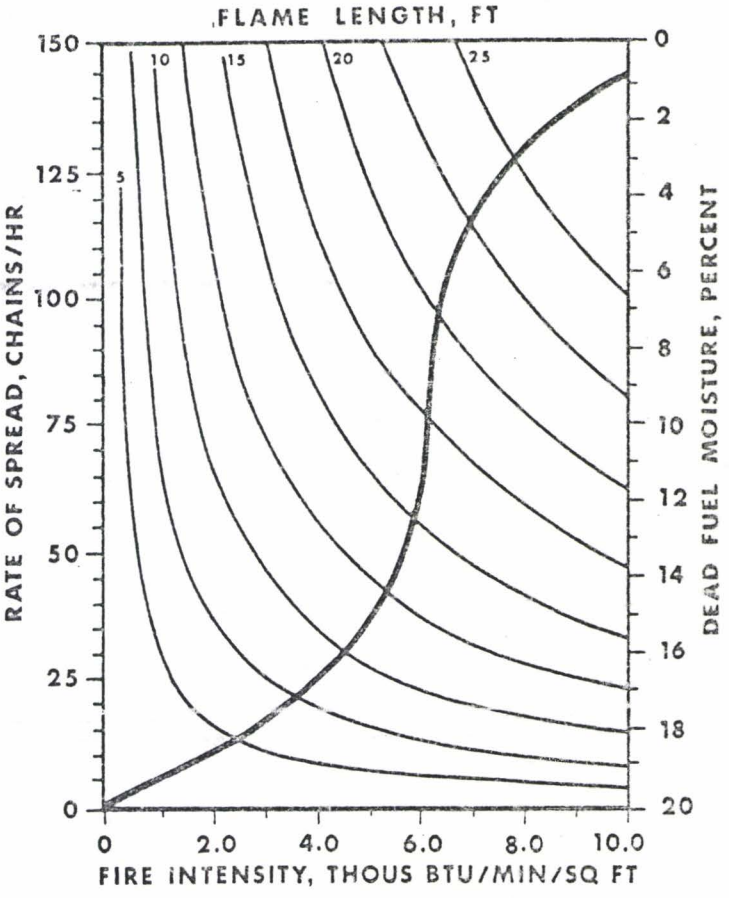


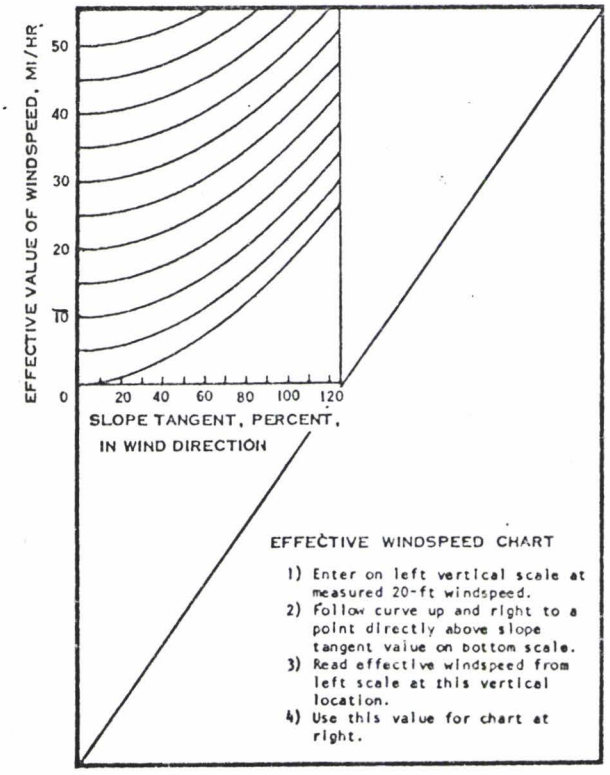


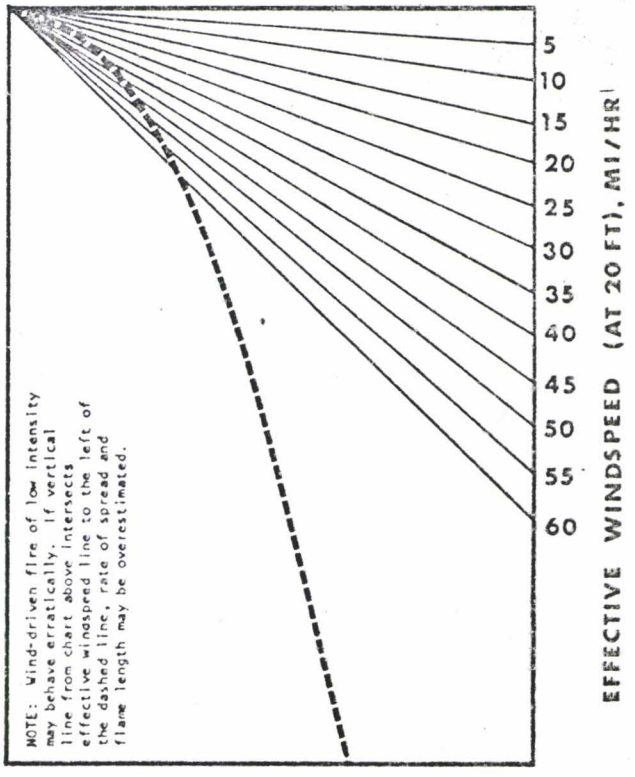

NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR
0
2
4
6
8
10
12
14
16
18

I. MEDIUM LOGGING SLASH-HIGH WINDSPEEDS

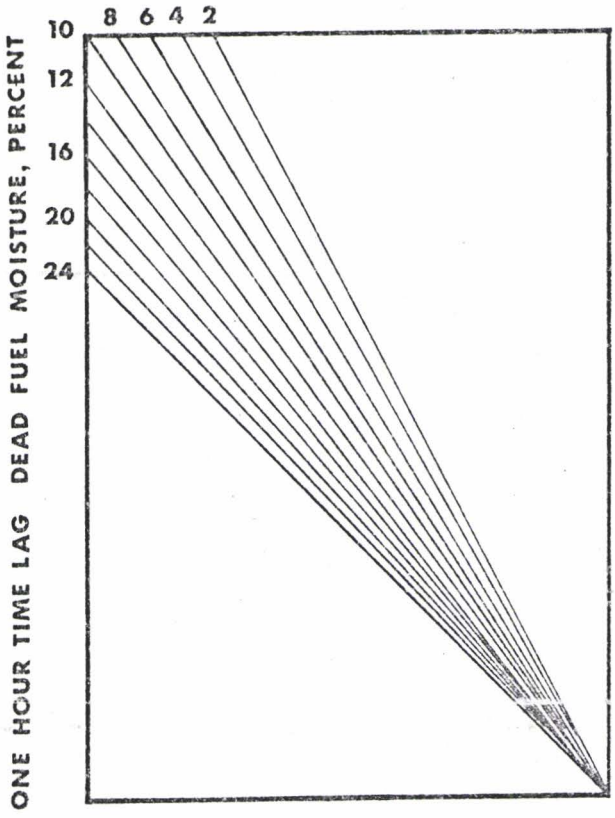


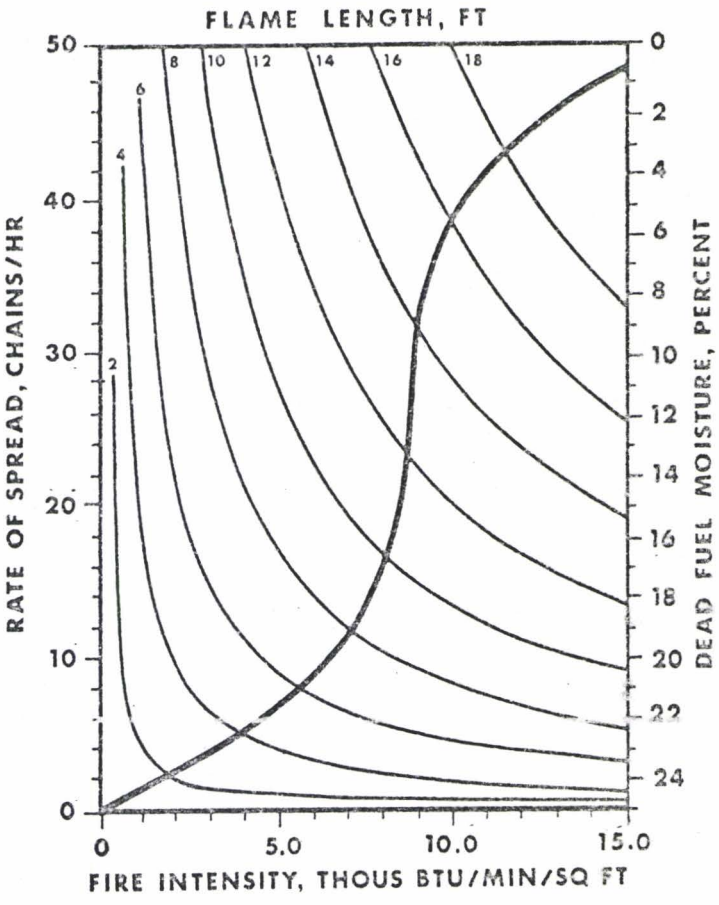


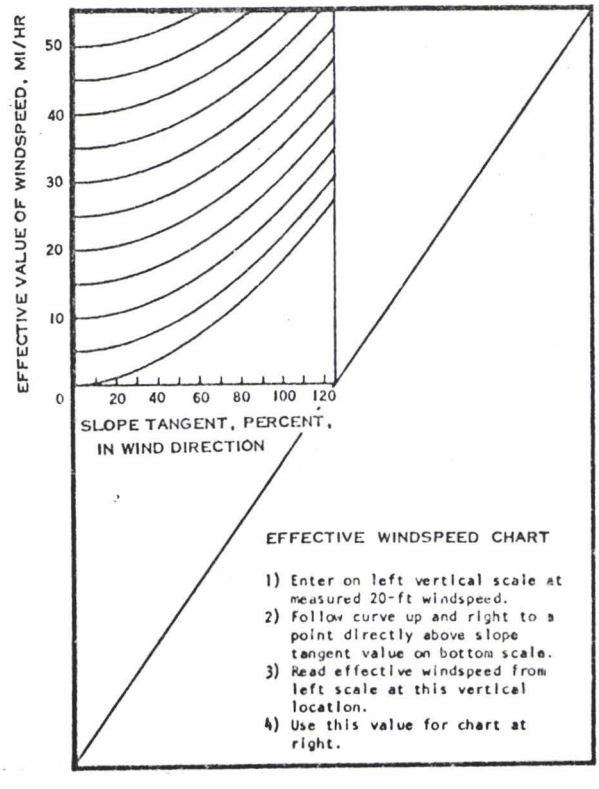


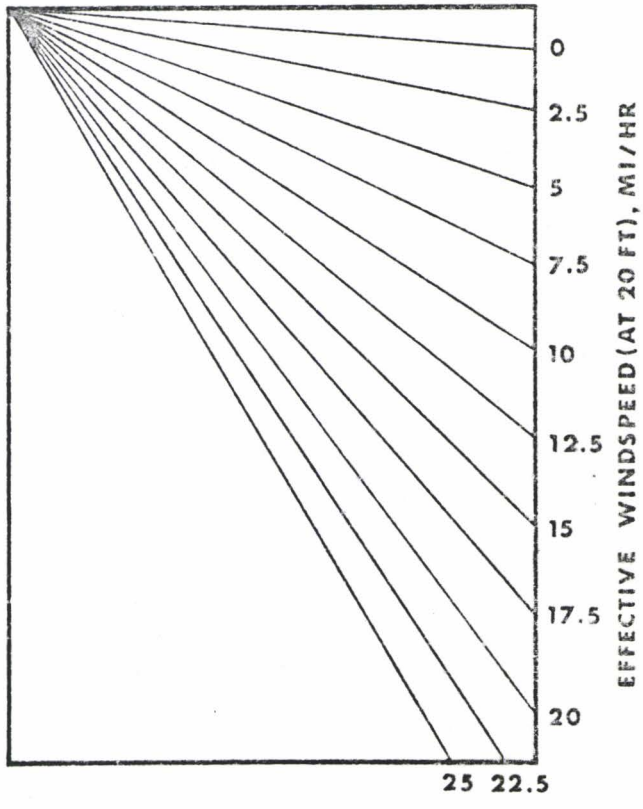


J. HEAVY LOGGING SLASH-LOW WINDSPEEDS

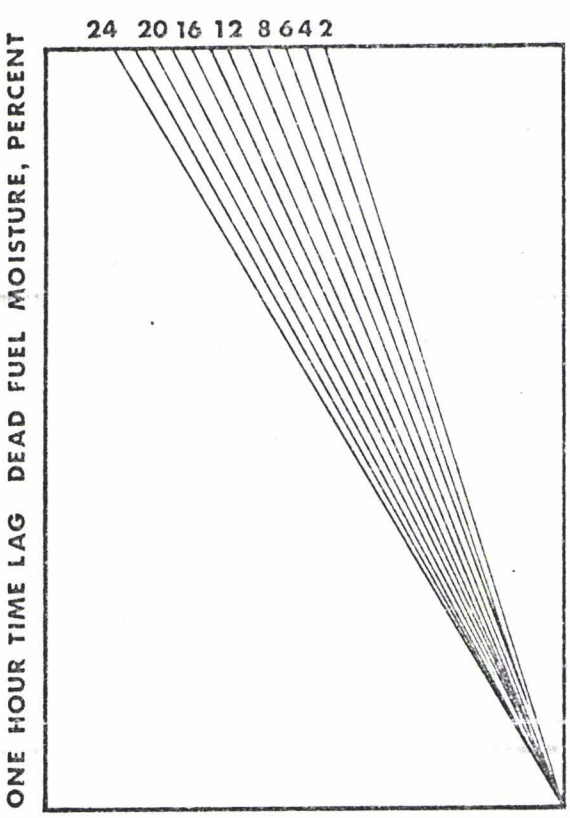


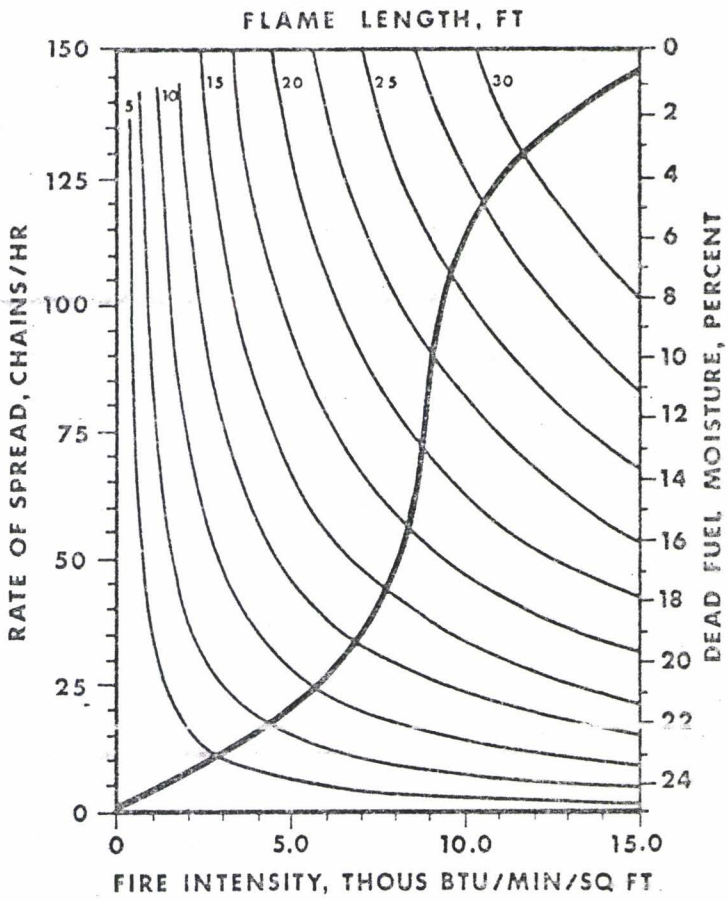


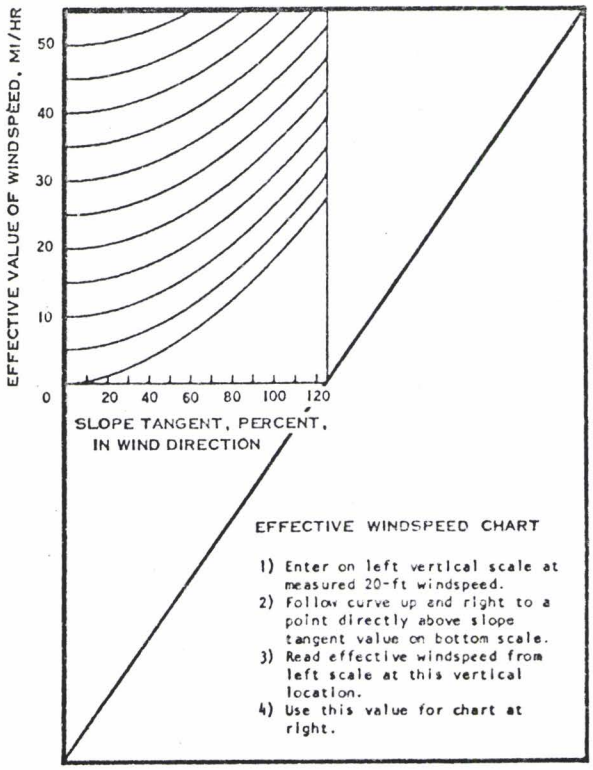

EFFECTIVE VALUE OF WINDSPEED, MI/HR
50
40
30
20
10
0
20 40 60 80 100 120
SLOPE TANGENT, PERCENT, IN WIND DIRECTION
EFFECTIVE WINDSPEED CHART
1) Enter on left vertical scale at measured 20-ft windspeed.
2) Follow curve up and right to a point directly above slope tangent value on bottom scale.
3) Read effective windspeed from left scale at this vertical location.
4) Use this value for chart at right.

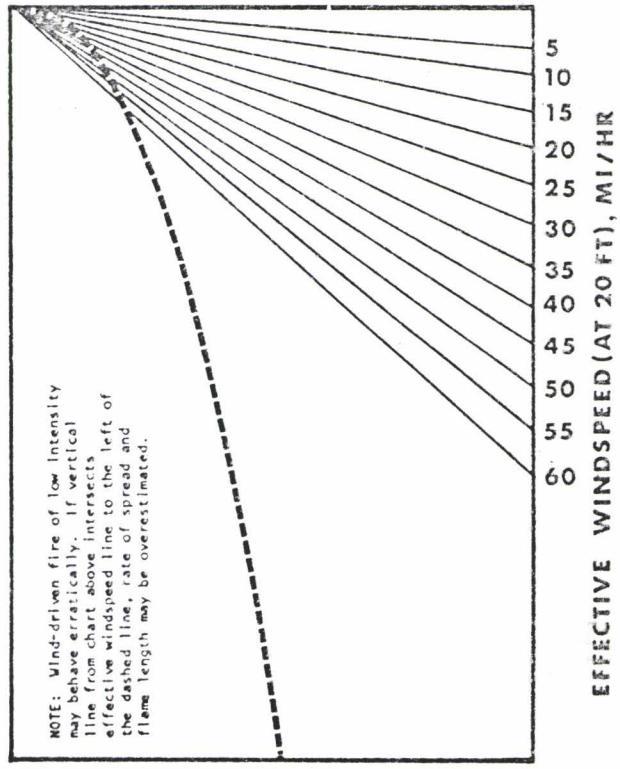


J. HEAVY LOGGING SLASH - HIGH WINDSPEEDS

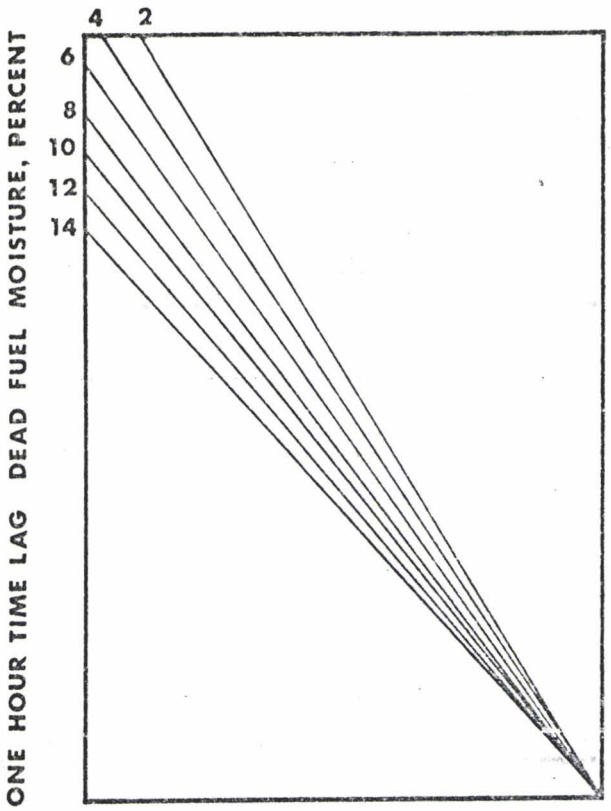


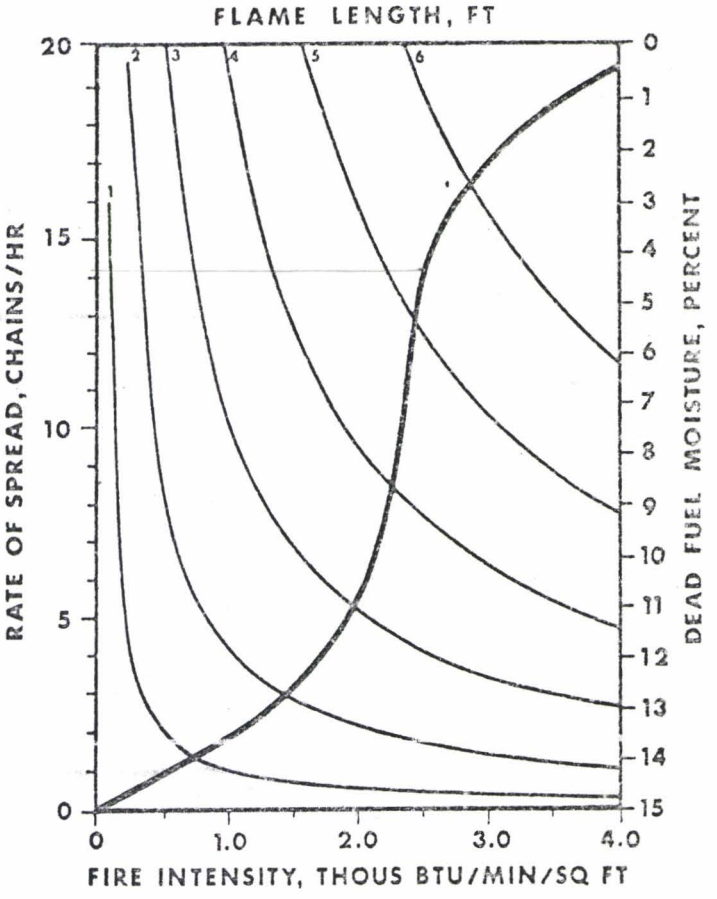


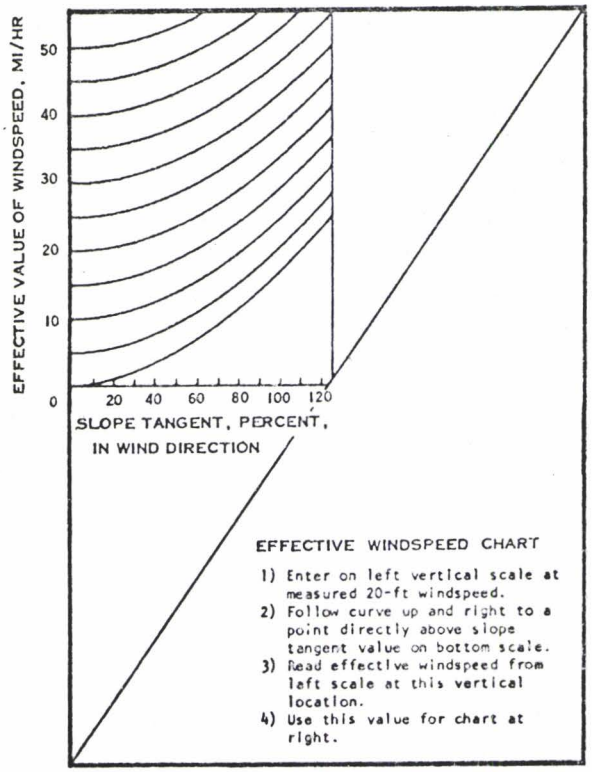

EFFECTIVE VALUE OF WINDSPEED, MI/HR
50
40
30
20
10
0
20 40 60 80 100 120
SLOPE TANGENT, PERCENT, IN WIND DIRECTION
EFFECTIVE WINDSPEED CHART
1) Enter on left vertical scale at measured 20-ft windspeed.
2) Follow curve up and right to a point directly above slope tangent value on bottom scale.
3) Read effective windspeed from left scale at this vertical location.
4) Use this value for chart at right.

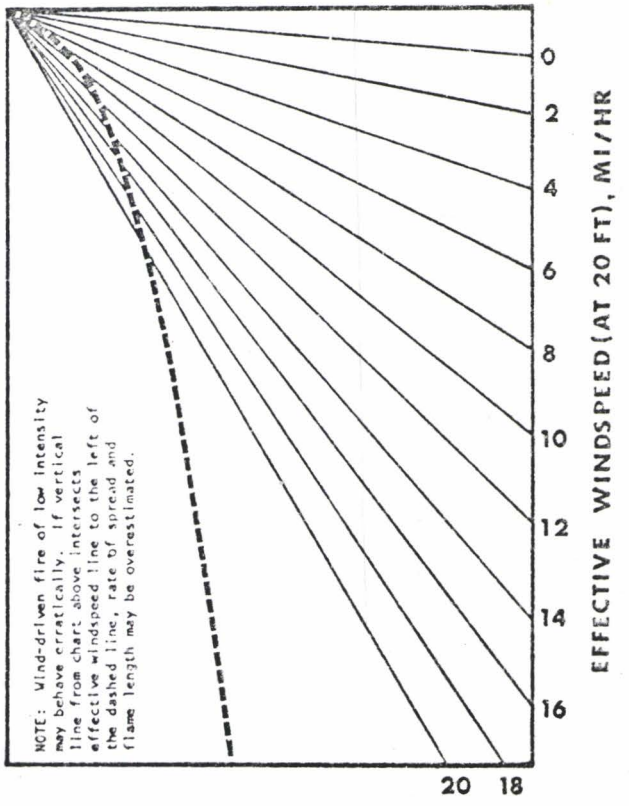


K. LIGHT LOGGING SLASH - LOW WINDSPEEDS

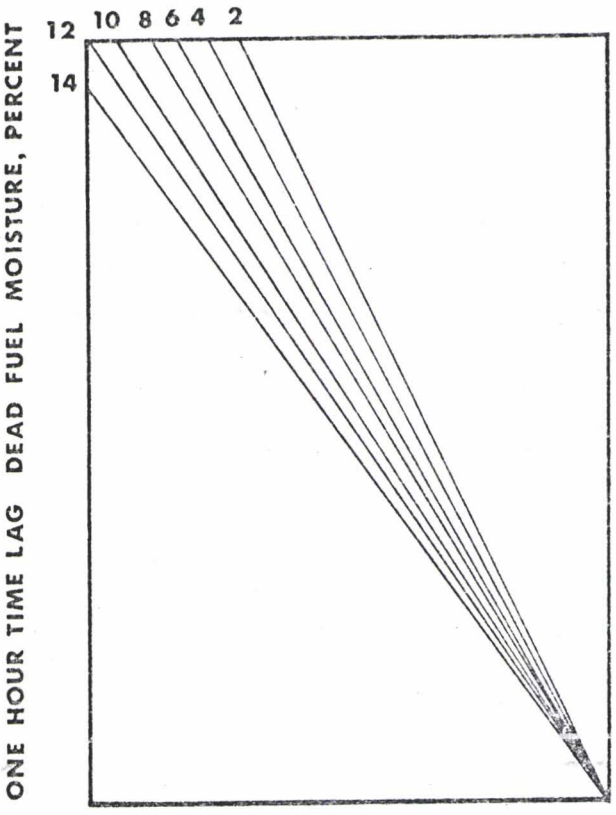


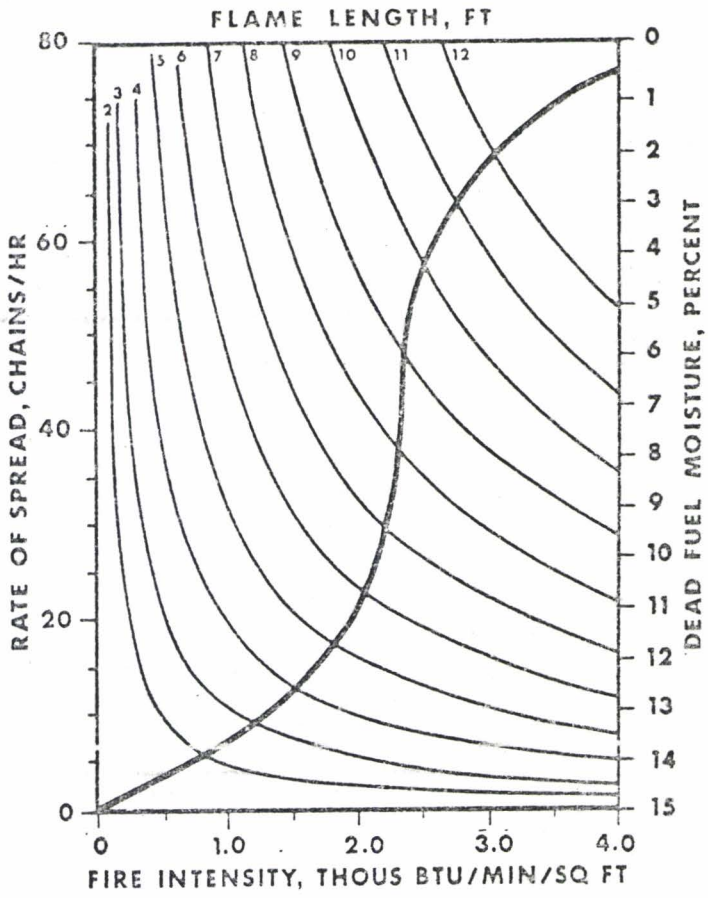


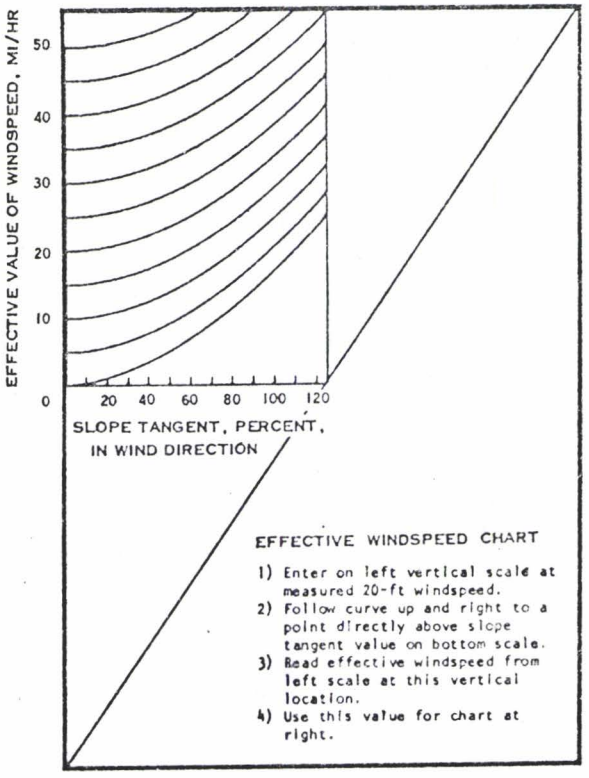


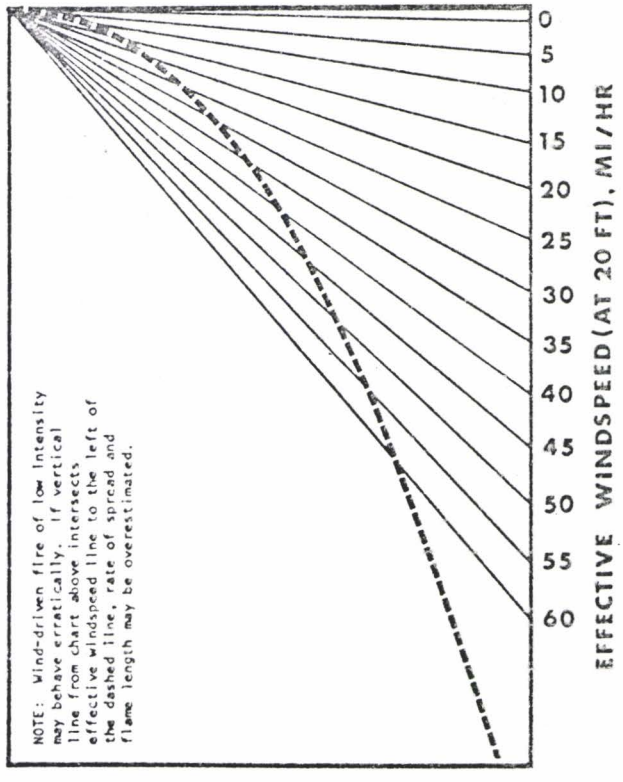

NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR
0
2
4
6
8
10
12
14
16
20
18

K. LIGHT LOGGING SLASH - HIGH WINDSPEEDS

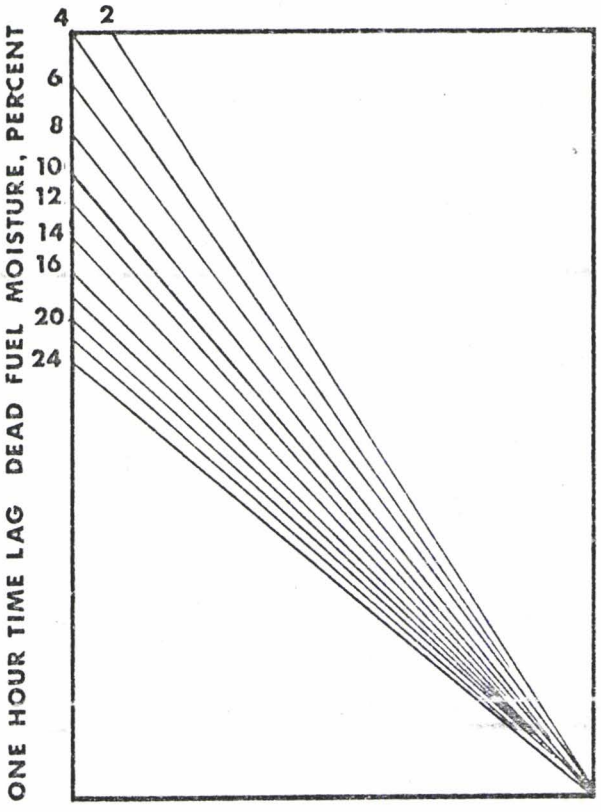


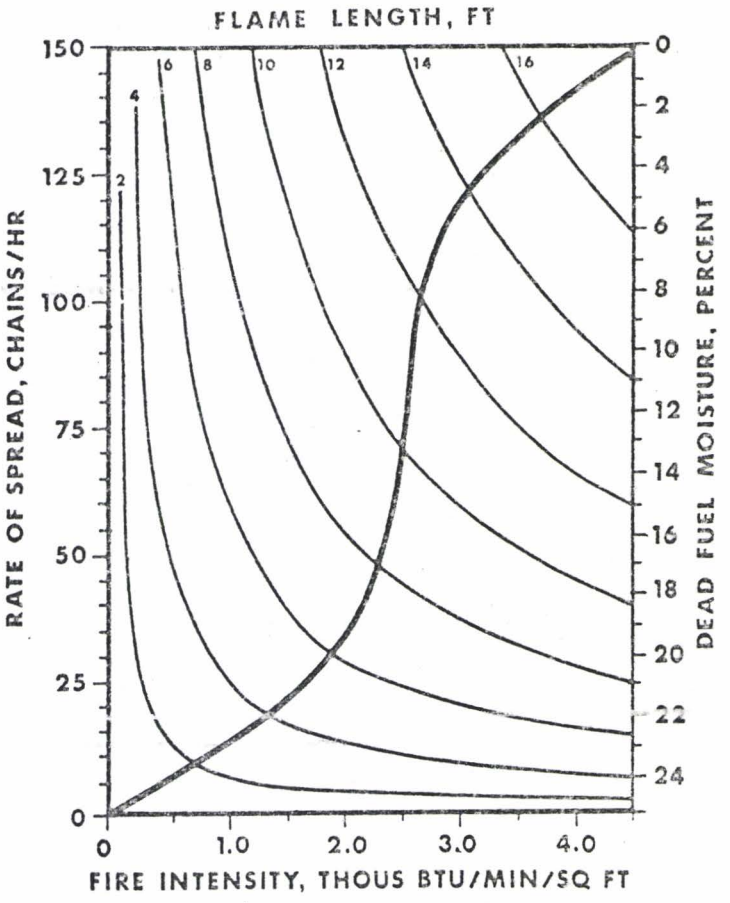


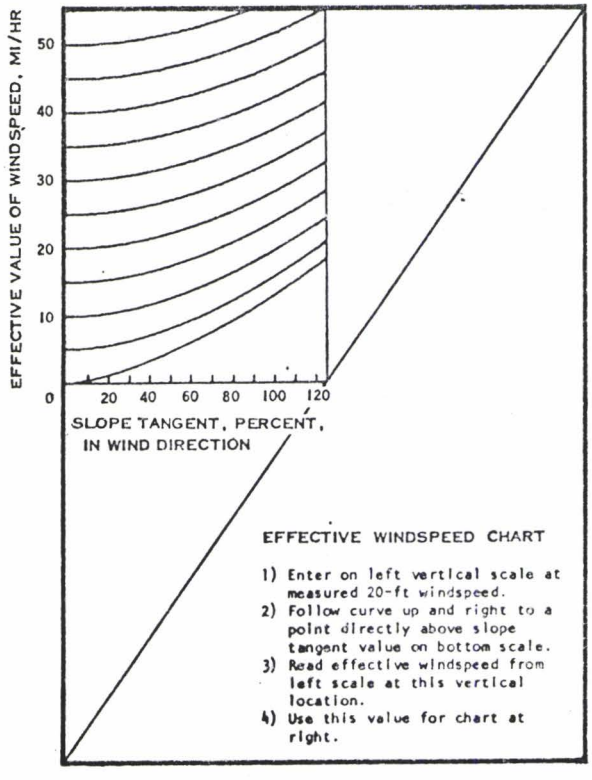


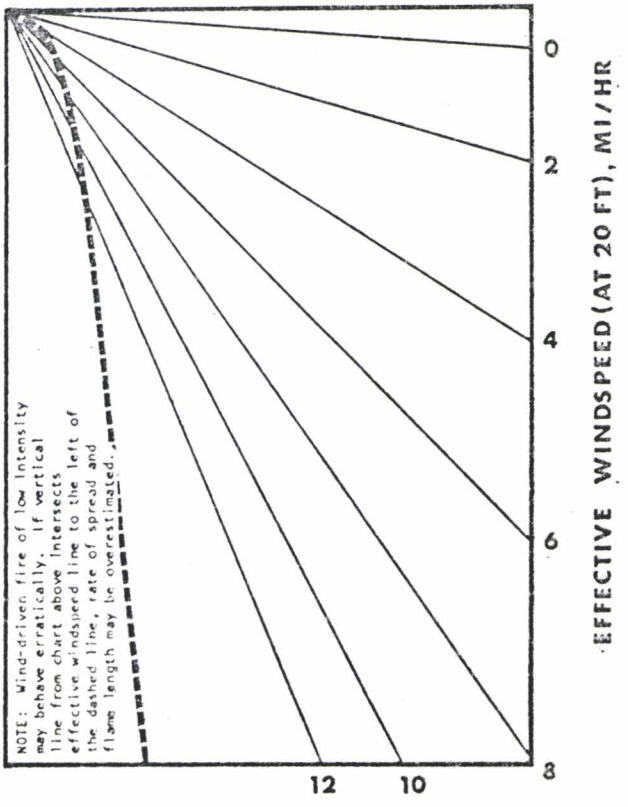


L. TALL GRASS (2.5 FT)-LOW WINDSPEEDS

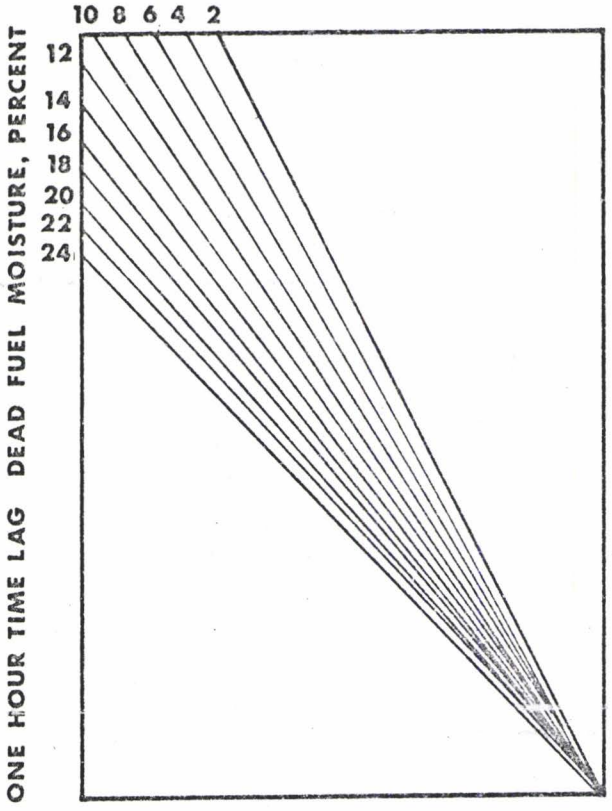


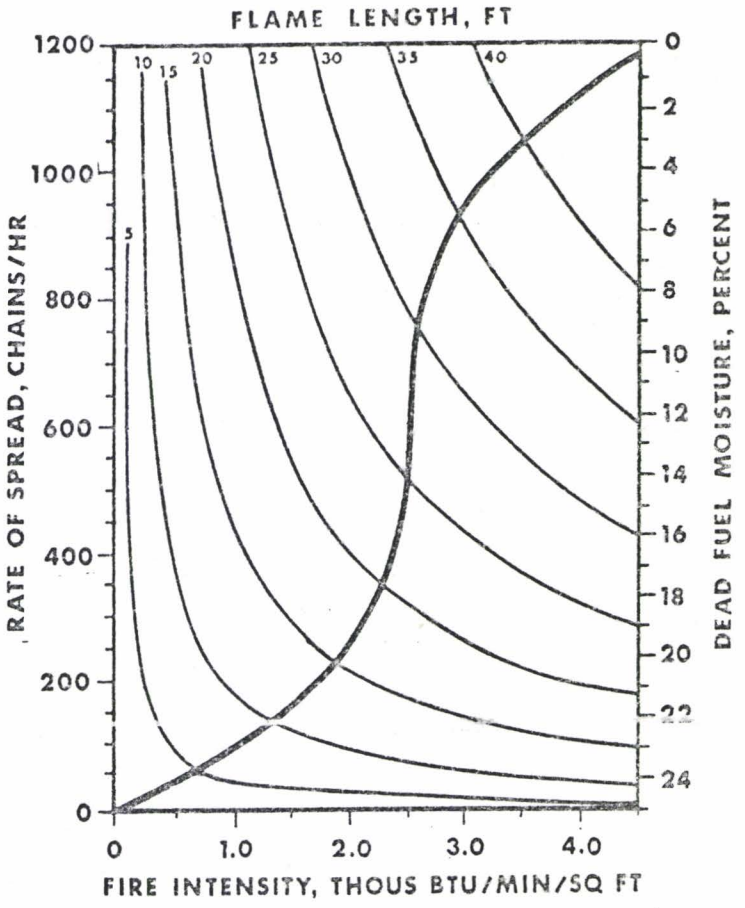


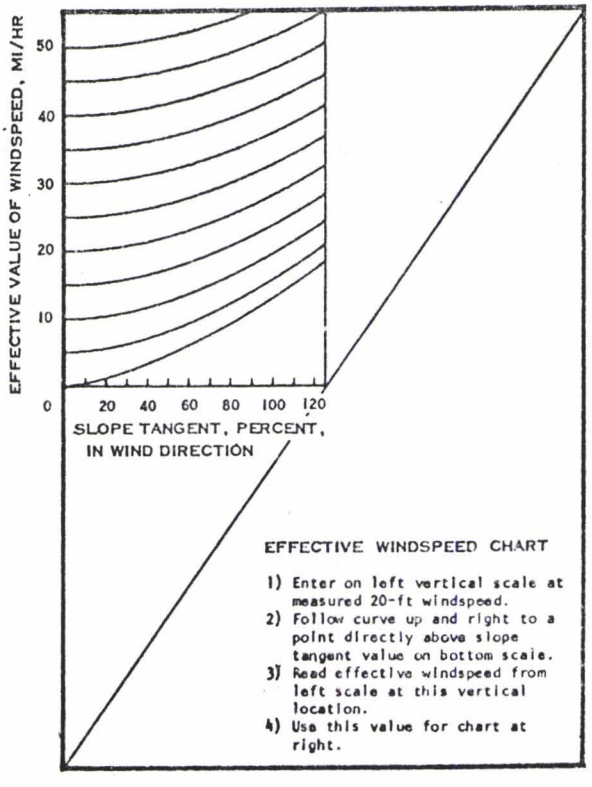


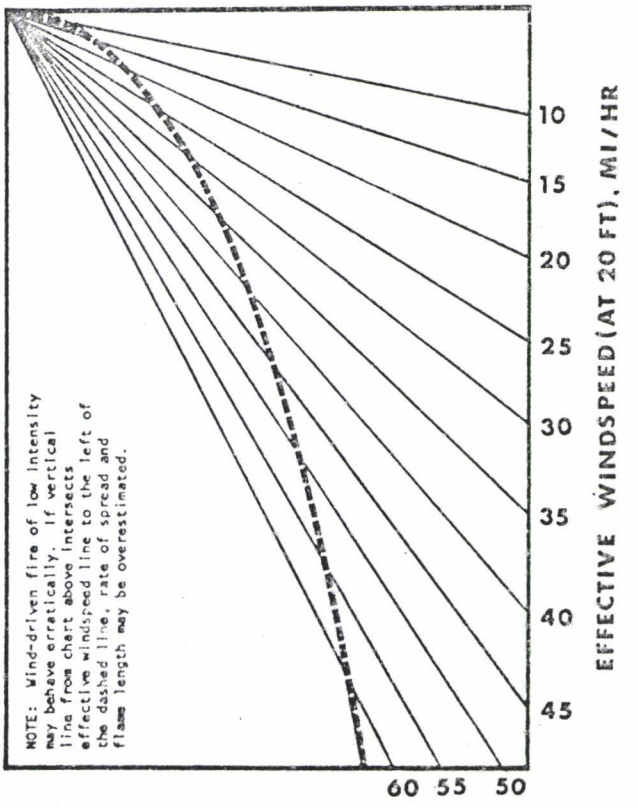

NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR
0
2
4
6
8
12
10

L. TALL GRASS (2.5 FT) - HIGH WINDSPEEDS

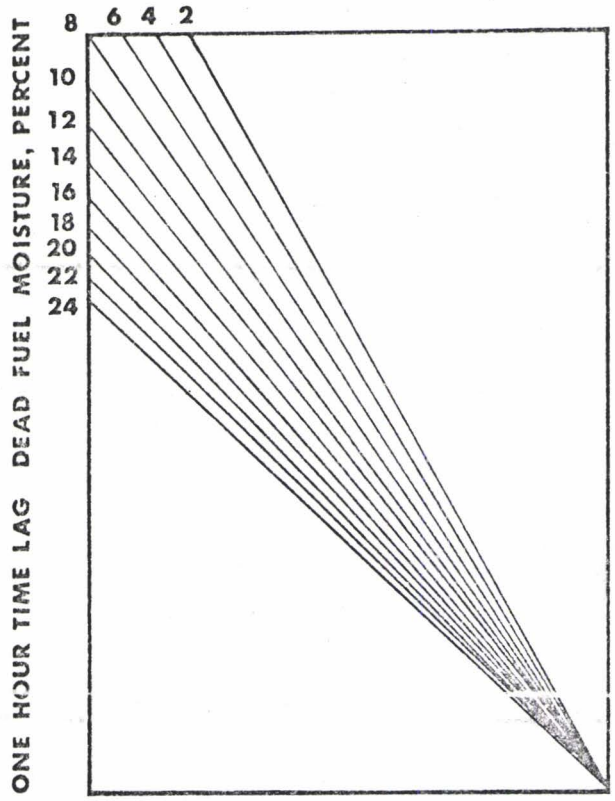


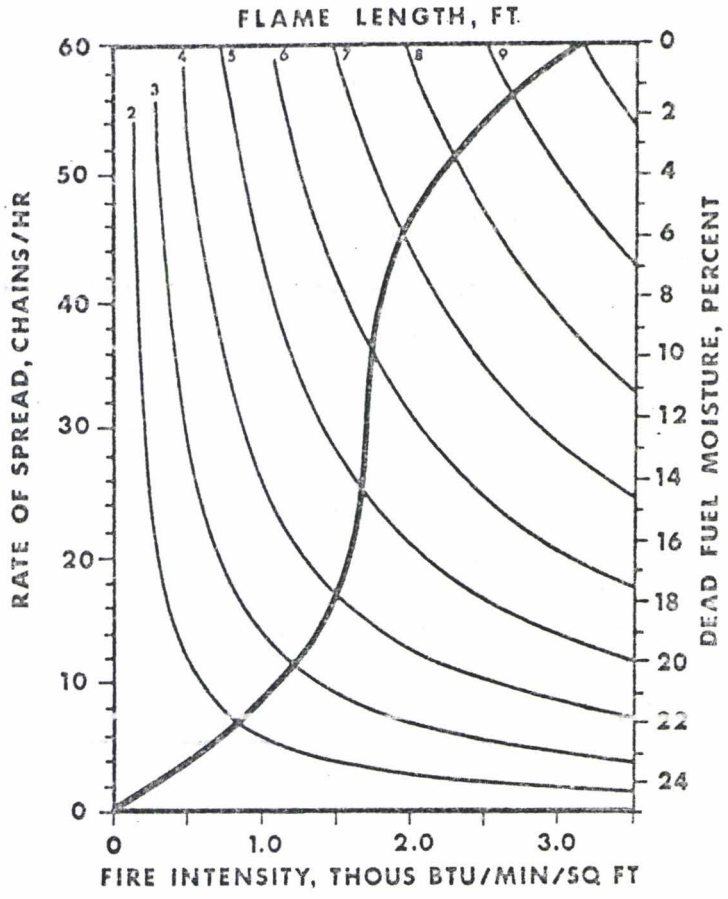


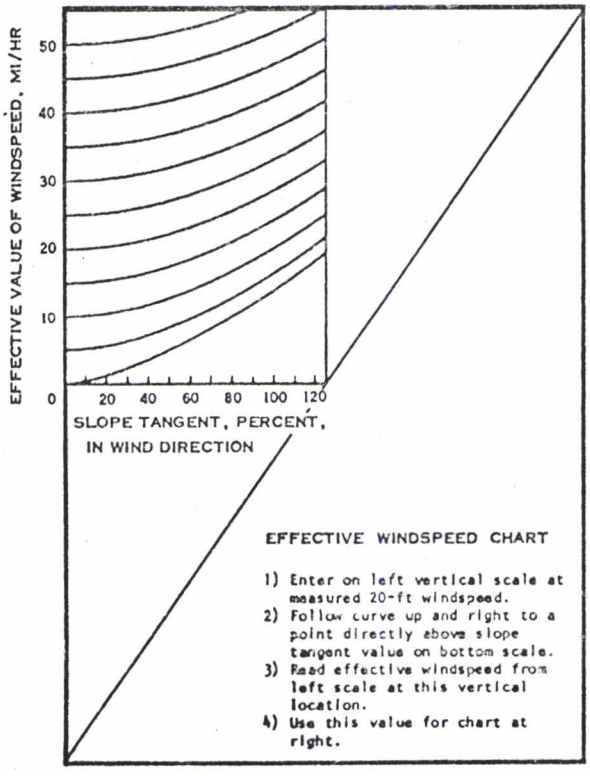


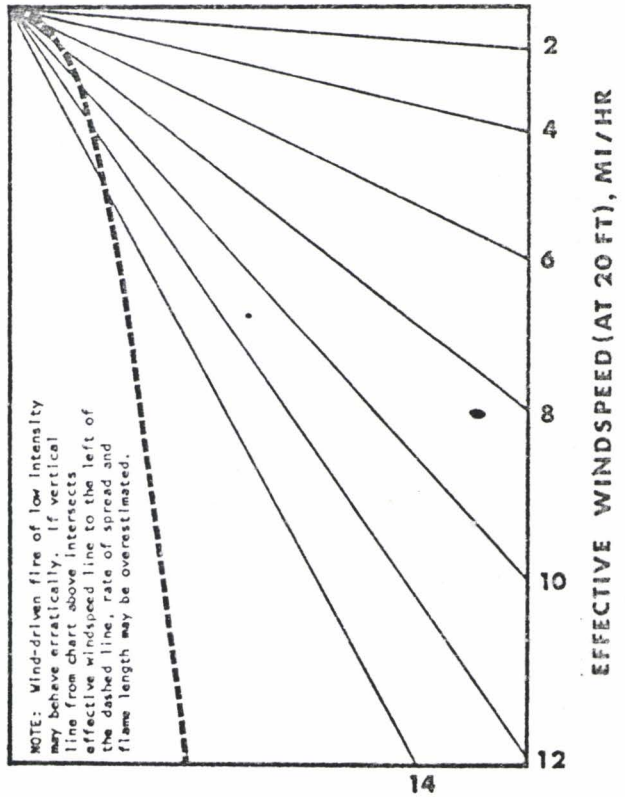

NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR
10
15
20
25
30
35
40
45
60
55
50

M. DORMANT BRUSH, HARDWOOD SLASH - LOW WINDSPEEDS

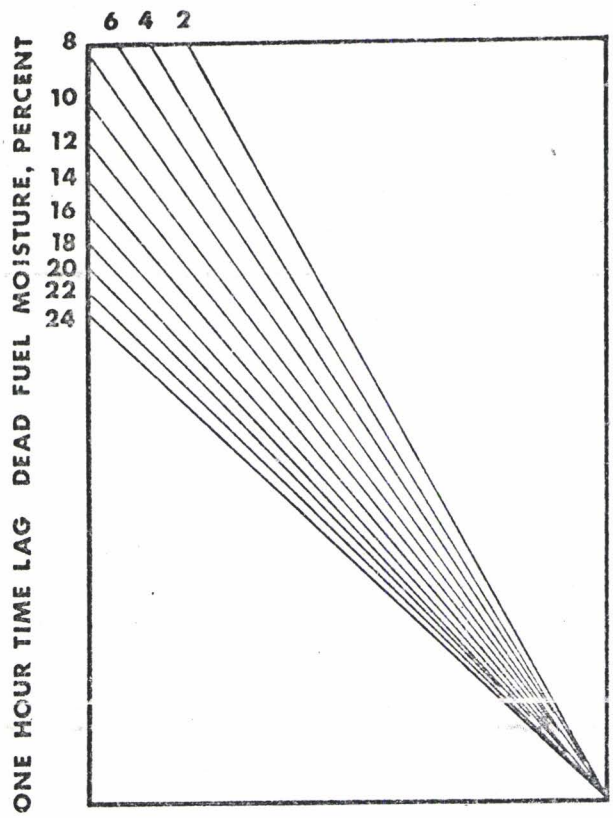


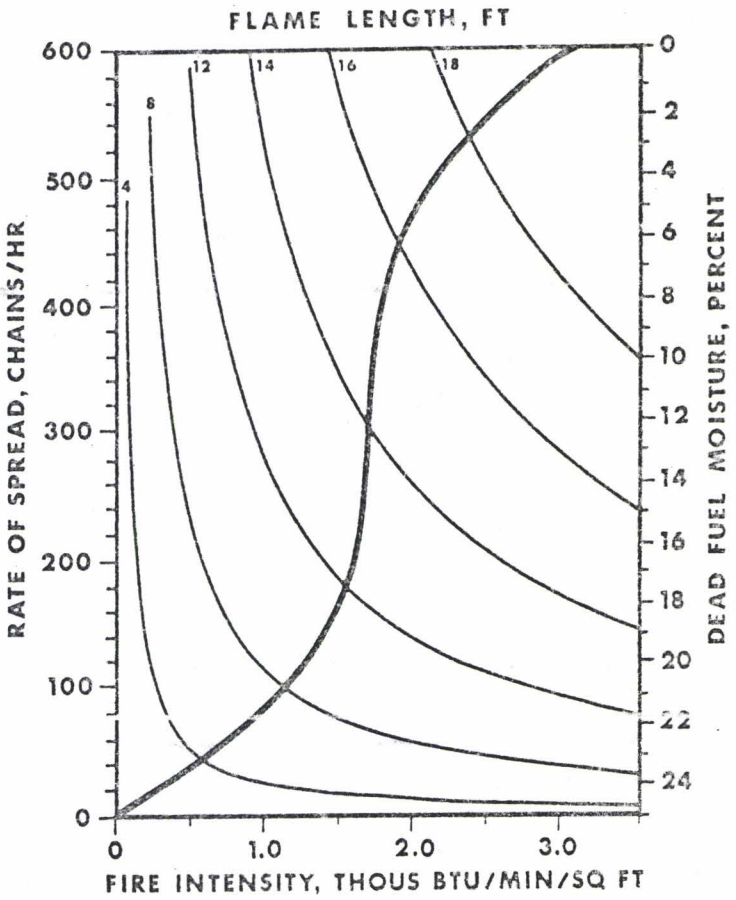


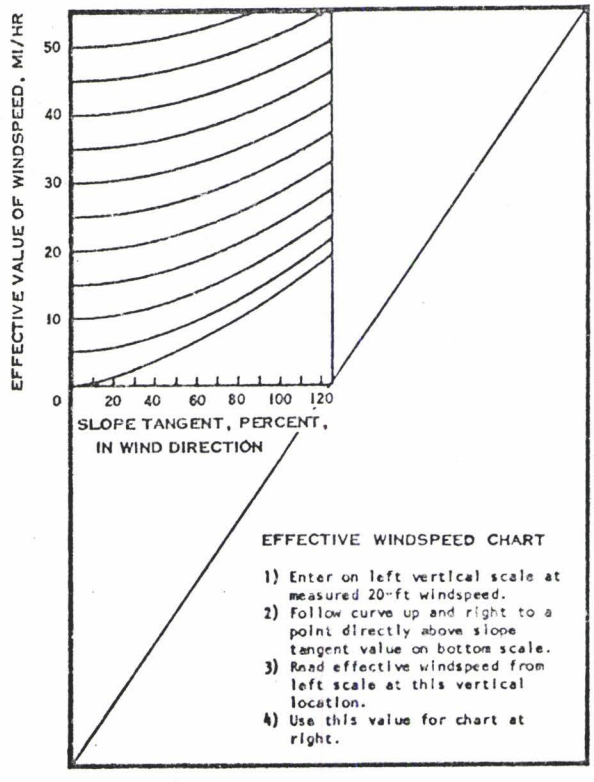


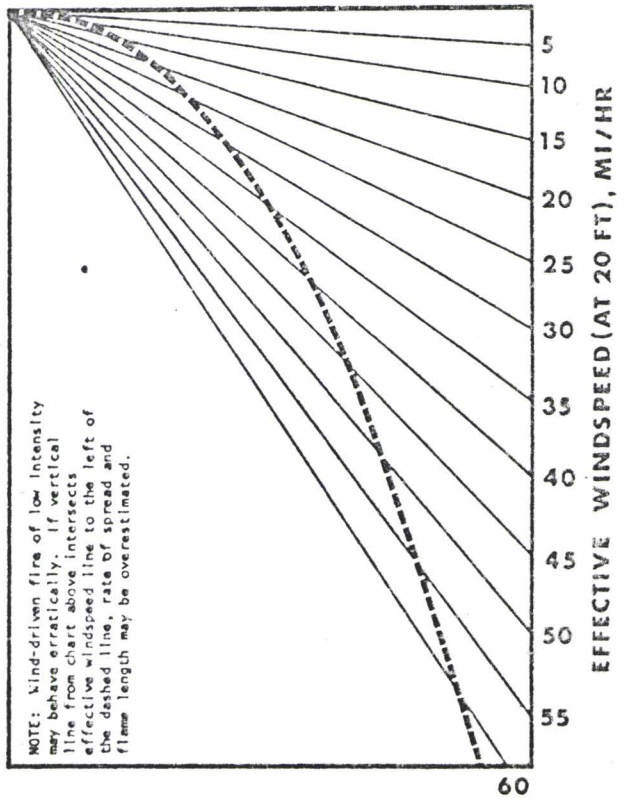

NOTE: Wind-driven fire of low intensity may behave erratically. If vertical line from chart above intersects effective windspeed line to the left of the dashed line, rate of spread and flame length may be overestimated.
EFFECTIVE WINDSPEED (AT 20 FT), MI/HR
2
4
6
8
10
12

M. DORMANT BRUSH, HARDWOOD SLASH-HIGH WINDSPEEDS









A P P E N D I X E S

APPENDIX A

GUIDE TO THE SELECTION OF FUEL MODELS

NOTE: This guide is taken largely from the National Fire- Danger Rating System[5/], because the fuel models herein are very similar to those in the NFDRS. But the methods of computation are somewhat different and the meaning and intended use of the results are not the same. The fact that this set of models is intended to represent the same sets of conditions as are represented in the NFDRS does not imply endorsement of the models or methods by the Forest Service, the Department of Agriculture, or the research work unit responsible for developing the National Fire-Danger Rating System. This document represents a research effort by the Northern Forest Fire Laboratory in an attempt to make broadly available the current state-of-the-art in fire behavior analysis, in an effort to assist those responsible for fire behavior predictions and to obtain from them commentary on the utility and accuracy of the methodology.

The following key should help in selecting the correct fuel model. Keep in mind that the models are not based on cover types, but on how much fuel, by classes, is present and how it is arranged. Rather diverse cover types are grouped together because they have similar fuel properties.

5/ Deeming, ibid.

Because data were not always available, fuel models could not be constructed specifically for several common wildland situations. In the following key, such situations are designated with an asterisk (*) and a "best fit" model is suggested.

FUEL MODEL KEY - 1972

I. The area is not timbered; less than one-third of the area is occupied by trees. (Stunted tree species and conifer reproduction are grouped with shrubs and called brush. Slash is not considered as brush.)

A. Grass and other herbaceous plants or mosses and lichens are the predominant fuel. Brush, slash and trees together occupy less than one-third of the area.

1. Fuel depth ~1 ft, short grass typically.....Model A

2. Tall grass (2.5 ft) thick-stemmed nonwoody cover dead only.....Model L

B. Grass and other herbaceous plants are not the predominant fuel.

1. Brush or tree reproduction makes up the predominant plant cover; occupies one-third or more of the area.

a. The foliage of the predominant woody cover species burns readily.

(1) The predominant cover occupies two-thirds or more of the area.

(a) One-third or more of the woody portion of plants is dead; much of it 2 inches in diameter or larger, or there is a duff/litter layer at least 3 inches deep. Cover must average 6 feet or more in height.....Model B

(b) The cover contains little dead woody fuel larger than 2 inches in diameter, and the duff/litter layer is less than 3 inches deep.....Model D

(2) The predominant cover occupies one-third but less than two-thirds of the area.....Model C*

b. The foliage of the predominant cover species does not burn easily.....Model F

2. Slash is the predominant fuel.

a. The foliage is still attached to the slash.

(1) Coniferous slash

(a) Light (40 tons/acre).....Model K

(b) Medium (120 tons/acre).....Model T

(c) Heavy (200 tons/acre).....Model J

(2) Hardwood slash.....Model M

b. The foliage is no longer attached to the slash; settling is evident.

(1) Herbaceous plants have invaded the area.....Model C*

(2) Brush has invaded the area--

both live foliage and dead fuel burn readily..Model D*

cover is dormant or live foliage does not burn readily.....Model M*

II. The area is timbered. One-third or more of the area is occupied by trees.

A. The area has been thinned or partially cut, leaving slash as the major fuel component.

1. Coniferous slash with needles attached.....Model B*

2. All hardwood slash or coniferous slash with needles no longer attached.....Model G

B. The area has not been thinned or partially cut.

1. Grass and other herbaceous plants are a common ground fuel; the canopy of the overstory is commonly "open".....Model C

2. Duff/litter, branchwood, and tree boles are the primary ground fuel; the canopy of the overstory is "closed" though openings may be common in the stand.

a. Two-thirds or more of the overstory consist of deciduous species.

(1) The overstory is dormant; the leaves have fallen and the leaf litter is not compact.....Model E

(2) The overstory is not dormant; or the leaf litter has been compacted by rain or snow.....Model H

b. One-third or more of the overstory consists of evergreen species.

(1) The overstory is mature or over-mature and is often decadent. There is an exceptionally heavy accumulation of branchwood, downed trees, and duff/litter on the forest floor.....Model C

(2) The overstory is immature or mature. There is only a nominal accumulation of debris on the forest floor.

(a) Brush or reproduction occupies less than one-third of the area.

(i) The ground fuel is primarily needles 2 inches or more long (most pines).....Model E*

(ii) The ground fuel is primarily needles less than 2 inches long.....Model H

(b) Brush or reproduction occupies one-third or more of the area.

(i) The foliage of the understory burns readily or needle drape is prevalent.....Model D*

(ii) The foliage of the understory does not burn readily and there is little or no needle drape.....Model F

APPENDIX B

THE FUEL MODELS

The descriptions of the fuel models used in constructing the nomographs are given in Table 1. The other variables needed to complete the descriptions for use in the fire spread model are held constant for the entire set. These variables are:

Ovendry fuel density	32 lb/ft^3
Heat of combustion (low heat value)	8,000 Btu/lb
Total mineral content	5.55 percent
Silica-free ash content (effective mineral content)	1.00 percent

Table 1.--Description of fuel models used in constructing nomographs.

Model	Typical fuel complexes	Total loading (dry)	Fuel depth	Dead fuel						Live fuel		Moisture of extinction dead fuel
				Surface/volume ratio			Ovendry loading			Surface/volume ratio	Ovendry loading	
				1 hr	10 hr	100 hr	1 hr	10 hr	100 hr			
		Tons/acre	Ft	----------Ft^{-1}--------			-------Lb/ft^2----------					Percent
A	Short grass	0.75	1.0	3,500			0.034					12
B	Chaparral	25.00	6.0	2,000	109	30	.230	0.840	0.092	1,500	0.230	20
C	Timber (Grass and Understory)	4.00	1.0	3,000	109	30	.092	.046	.023	1,500	.023	15
D	Easily-burned mixed cover	6.00	2.5	1,750	109	30	.052	.086	.069	1,550	.017	40
E	Hardwood litter	15.00	.2	2,500	109	30	.134	.019	.007			25
F	Brush (not chaparral)	6.00	2.0	2,000	109		.046	.023		1,500	.092	20
G	Timber (Litter and Understory)	30.00	1.0	2,000	109	30	.138	.092	.230	1,500	.092	25
H	Closed timber litter	15.00	.2	2,000	109	30	.069	.046	.115			30
I	Medium logging slash	120.00	2.3	1,500	109	30	.184	.644	.759			20
J	Heavy logging slash	200.00	3.0	1,500	109	30	.322	1.058				25
K	Light logging slash	40.00	1.0	1,500	109	30	.069	.207	.253			15
L	Tall grass	3.00	2.5	1,500				.138				25
M	Dormant brush, hardwood slash	6.00	2.5	1,750	109	30	.069	.069	.092			25

APPENDIX C

BASIS FOR CONSTRUCTION OF THE NOMOGRAPHS

I. Mathematical Basis

The nomographs represent a graphical means of performing the computations specified by Rothermel[6] for determining reaction intensity and rate of spread, with minor modifications. The computations were performed July 25, 1974, on the CDC 7600 computer at the Lawrence Berkeley Laboratories Computer Center (BKY) located on the campus of the University of California at Berkeley. The program used was the FIREMODS library of computer subroutines maintained on disk file storage at BKY by the Northern Forest Fire Laboratory.

The modifications of the equations[7] which are significant in the computations resulting in these nomographs are outlined briefly below. (Other revisions have been made, but are inconsequential for these computations.)[8]

1. The dry-weight loading of any particular fuel element, W_o, includes the noncombustible mineral fraction, S_T. The loading of combustible fuel is $W_o(1 - S_T)$, not $W_o/(1 + S_T)$ as in Rothermel.[9]

---

[6] Rothermel, op.cit.

[7] Rothermel, ibid.

[8] Frank A. Albini. FIREMODS library subroutines. Unpublished manual available on request to Northern Forest Fire Laboratory, Missoula, Mont.

[9] Rothermel, op.cit.

2. The equation for reaction velocity, Γ',[10] includes an exponent A, calculated from equation 39:

$$A = (4.77\ \sigma^{0.1} - 7.27)^{-1}$$

In the computer-based model this equation is replaced by

$$A = 133\ \sigma^{-0.7913}$$

to prevent divergence of results as σ approaches $(7.27/4.77)^{10}$. The differences are small but noticeable between the two methods of computation.

3. The calculation of the moisture of extinction of the live fuel loading is described by equation 88,[11] which can be written as

$$(M_x)_{living} = 2.9\ W(1-(M_f)_{dead}/0.3) - 0.226 \qquad \text{(minimum value 0.3)}$$

where

$(M_x)_{living}$ = Moisture of extinction of living fuel

W = Ratio of "fine" fuel loadings, dead/living

$(M_f)_{dead}$ = Moisture content of "fine" dead fuel.

---

[10] Rothermel, ibid.

[11] Rothermel, ibid.

In the computer-based model this equation is replaced by

$$(M_x)_{living} = 2.9\ W'(1 - (M'_f)_{dead}/(M_x)_{dead}) - 0.226$$

(minimum value $(M_x)_{dead}$)

where

$$W' = (\Sigma_{dead} W_{o,j} \exp(-138/\sigma_j))/(\Sigma_{live} W_{o,j} \exp(-500/\sigma_j))$$

$$(M'_f)_{dead} = (\Sigma_{dead} W_{o,j} M_{f,j} \exp(-138/\sigma_j))/(\Sigma_{dead} W_{o,j} \exp(-138/\sigma_j))$$

and

$W_{o,j}$ = dry weight loading of size class j

σ_j = surface/volume ratio of size class j

$M_{f,j}$ = moisture content of size class j

The exponential weighting factors, developed by W.H. Frandsen,[12] make explicit the calculation of "fine" fuel properties for an arbitrary fuel description, and replacement of 0.3 by $(M_x)_{dead}$ gives stable behavior to the models over a wide range of moisture-of-extinction of the dead fuel.

---

[12] William H. Frandsen. Unpublished data on file at Northern Forest Fire Laboratory, Missoula, Mont.

4. In Rothermel's equation 58, the reaction intensity of the dead and living fuel categories were combined by forming a weighted average where the weighting factor was the fraction of fuel surface area per unit of ground area contributed by each category. In the computer-based model the intensities are simply added together. This change is due to a revision in the method of categorizing fuel components; only two categories (live and dead) are now employed, while at the time Rothermel published his findings,[13] it was felt that categorization by species might be more useful.

II. Nomograph Organization

The nomographs are organized into three functional quadrants: The two right-hand quadrants, the upper left-hand quadrant, and an auxilliary working chart inset in the lower left-hand quadrant above the lone index line.

The upper right-hand quadrant represents a graph of reaction-intensity (right horizontal axis) versus dead-fuel-moisture (far right upper vertical axis). For the models presented here, the dead fuel moisture can be taken to be the 1-hour fuel moisture in all cases except models I, J, and K, for conifer slash and models D and M for mixed cover and hardwood slash. For these models one can use an average moisture computed from Rothermel's[14] area-weighted formula:

$$(M_{fuel})_{dead} = 0.76(M_{1\text{-hr}}) + 0.18(M_{10\text{-hr}}) + 0.06(M_{100\text{-hr}}) \quad \text{Models I,J,K}$$

or

$$(M_{fuel})_{dead} = 0.89(M_{1\text{-hr}}) + 0.09(M_{10\text{-hr}}) + 0.02(M_{100\text{-hr}}) \quad \text{Models D,M}$$

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[13] Rothermel, op.cit.

[14] Rothermel, ibid.

For those models which include live fuel, only the foliage moisture is used and only the foliage component is included in the fuel loadings.

The lower right-hand quadrant represents the combined effect of wind and slope on amplifying the propagating flux, which is proportional to the reaction intensity. The wind coefficient, ϕ_W, and the slope coefficient, ϕ_S, are combined using the auxilliary working chart in the lower left-hand quadrant to produce an effective windspeed which, when used in the formula for the wind coefficient, produces an amplification factor equal to the sum of the two coefficients:

$$\phi_W \text{ (effective windspeed)} = \phi_W \text{ (measured windspeed)} + \phi_S \text{(slope)}$$

The lower right-hand quadrant is thus a plot of straight lines of slope $(1 + \phi_W)$ relating amplified propagating flux to reaction intensity. In all cases it is assumed that the windspeed at midflame height is half the measured windspeed at 20 feet above ground.

The lower left-hand quadrant is nonfunctional serving only to translate the propagating flux to the horizontal axis of the upper left-hand quadrant.

The upper left-hand quadrant represents a plot of the rate-of-spread (center vertical axis) versus the propagating-flux (left horizontal axis, running right to left). The relationship plotted is:[15/],[16/]

$$R = I_p/Q_{ig}$$

[15/] Rothermel, ibid.

[16/] William H. Frandsen. Fire spread through porous fuels from the conservation of energy. Combustion and Flame 16:9-16, 1971.

where R is spread rate, I_p is propagating flux, and Q_{ig} is the bulk heat of preignition. For models which have dead fuel only, Q_{ig} is simply a function of the dead fine fuel (1-hr) moisture content.

For models which contain both live and dead fuel components, Q_{ig} is the function of both the dead fine fuel moisture and the live foliage moisture, so the slope of the appropriate line ($1/Q_{ig}$) relating the two variables must be constructed for each combination of interest. Since the right-hand vertical axis is essentially the 1-hour timelag dead fuel moisture for these models, a curve for constant live foliage moisture can be constructed in the upper left-hand quadrant which represents the locus of end points of straight lines of slope ($1/Q_{ig}$) drawn from the origin to the vertical location of the dead fuel moisture. This allows the simple construction of the appropriate straight line of slope $1/Q_{ig}$ for the combination of live and dead fuel moistures.

The flame length curves in the upper right-hand quadrant are based on the simple approximation for depth of flaming zone, D,

$$D = (\text{rate of spread}) \times (\text{flaming zone residence time}) = Rt_R$$

where

$t_R = 384/\tilde{\sigma}$ = particle residence time in flaming zone, minutes.

The correlation of particle size, as represented by $\tilde{\sigma}$, a composite surface/volume ratio for the fuel bed, with flaming zone residence time is due to Anderson.[17]

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[17] Hal E. Anderson. Heat transfer and fire spread. USDA For. Serv. Res. Pap. INT-69, 20 p., illus., 1969.

The product of flaming zone depth, D, and reaction intensity, I_R, represents an approximate value of Byram's fireline intensity, I.

$$I = I_R D$$

This intensity can be used to estimate flame length, L, from the correlation equation[18]:

$$L = 0.45\ I^{0.46} \quad \text{L in ft, I in Btu/ft/sec)}$$

Combining these equations yields a family of hyperbole of the form

$$RI_R = K(L)^{1/0.46}$$

where K is a proportionality constant incorporating the numerical factors and rationalizing the systems of units employed in the above equations.

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[18] Arthur A. Brown and Kenneth P. Davis. Forest fire control and use. 686 p. McGraw-Hill Brook Co: New York. 1973.